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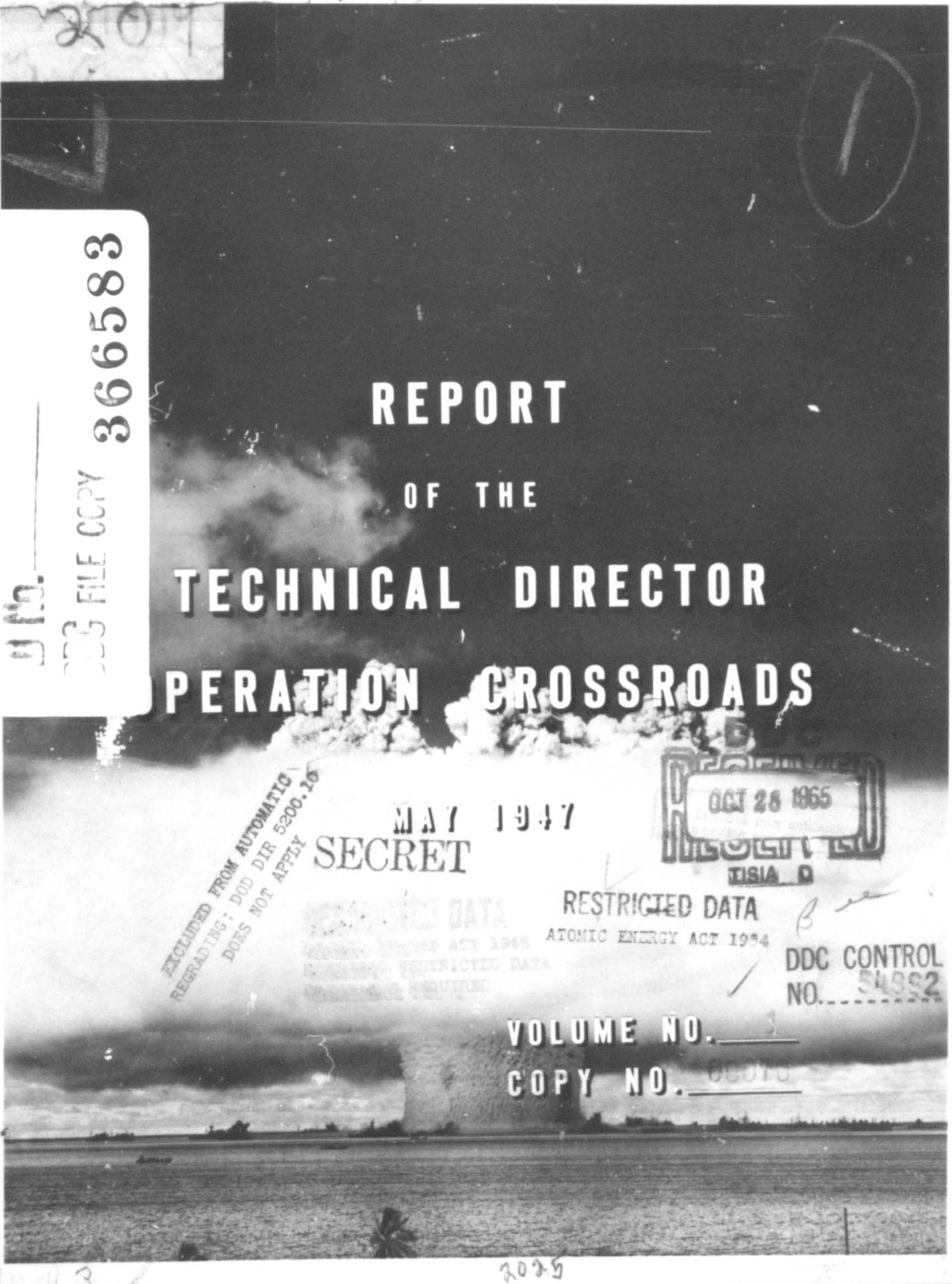

REPORT
OF THE
TECHNICAL DIRECTOR
OPERATION CROSSROADS

MAY 1947

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Report of the

TECHNICAL DIRECTOR, VOLUME I (U). ⑧

⑥ OPERATION CROSSROADS.

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Director
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Washington, D. C. 20301

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TECHNICAL STAFF
Navy Department
Washington, D.C.

1 December 1946

MEMORANDUM.

From: Technical Director.
To: Deputy Task Force Commander for Technical Direction.

Subj: Report on Instrumentation Program of Technical Staff.

Encl: (A) Copy of subject report.

1. Herewith is submitted the report of the Technical Director on the instrumentation program. This report is intended to summarize and analyze the objectives and results of the program to a degree that should be useful for staff information, for the Historian's Office and for the Joint Chiefs of Staff.

2. Final reports are now being received for all instrumentation activities. Copies of such final reports as are now available will be submitted separately at this time and others will be submitted as they are completed.

3. It is a pleasure at this time to express my appreciation and that of all 013 personnel for the consideration, assistance and support received from the Task Force and from you personally. It was a great experience and a privilege to be associated with you. Your sympathetic leadership was of incalculable value to the success of the program and a great contribution to the advancement of relations between civilian scientists and service personnel.

Ralph A. Sawyer
R. A. SAWYER

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INTRODUCTION

The instrumentation program of Operation Crossroads probably comprised the most extensive and elaborate program of experimental measurement and observation ever undertaken in the field. In all some 500 scientists and technical men, including service and civilian personnel, participated. They were assisted by at least an equal number of enlisted and civilian aides who acted as work parties, boat crews, clerical, and laboratory aides. These groups and individuals came from government agencies, the armed forces, universities, and other activities. Major groups, for example, came from the Naval Research Laboratory, Naval Ordnance Laboratory, David Taylor Model Basin, University of Washington, Wright Field, and Los Alamos Laboratory of the Manhattan Engineer District. Smaller groups and individuals came from dozens of schools and establishments.

Because of the short period allowed for preparation (originally only from 7 Jan 46 when the details of the program were worked out in a large conference, until 20 Mar 46 when the laboratory ships were to sail), it was necessary to the maximum extent possible to use or modify existing equipment and to call on existing agencies to furnish specialized groups and to undertake specific assignments. Thus, the Bureau of Ordnance, USN, undertook to look after all shock and blast effects in free air and water; and the Bureau of Ships, USN, undertook to look after blast, acceleration, displacement and similar measurements in and near ships. The Army Air Forces and the Navy Photographic Service divided the major photographic assignments. The organization chart Appendix II of Annex G shows in general how the various tasks were apportioned, while the individual project sheets of the Annex show specifically how each assigned measurement was carried out.

The major outline of the instrumentation program was laid out in conferences held in the Navy Department in late December 1945 and early January 1946 in which representatives of the Manhattan District and of the interested service agencies participated. Most of the groups and agencies involved set up planning and technical committees to work out details. The final instrumentation plan was in some respect a compromise between those who felt that the prime object of the test was to observe the effect of the bomb on naval vessels and that consequently little instrumentation was needed other than to determine the efficiency of the bomb and its position; and those, on the other hand, who felt that the test was an opportunity to try out nearly every measuring device ever know to science. The final decision, which was fairly closely adhered to, was that measurements should be of a practical nature, as opposed to those of purely scientific interest. Plans were made to gather data which would be (1) useful to designers of ships and ordnance material in assessing damage from and designing protection against atom bombs, (2) valuable in determining the nature, range, and duration of radiation danger from both types of burst and the best protection from it, (3) necessary to determine the bomb efficiency, burst location, wave formation, and ship movement, (4) helpful in providing counter intelligence means. Most of the measurements in Annex G to the Operations Plan will be found to fall into these categories.

A further consideration in planning the instrumentation program arose from the facts that the bomb might miss the target in Test A, that it might vary considerably in efficiency, and that some of the instruments might fail because of mechanical, time signal, or weather difficulties. Several methods were therefore provided for most determinations, and the number of each type of instrument and the overlapping of instrument ranges were greater than would have been necessary in a more accurately predictable test, or one in which a repetition was possible or likely. In Test A for example 200 cameras, 850 ball crusher gauges, 300 5 gallon cans, 400 photographic badges to measure radiation, and 5000 sulphur capsules were used. The total number of other instruments and gauges employed was above 5000. The wisdom of this procedure was amply proven in Test A, where, in spite of timing difficulties and error in drop, adequate data on all needed quantities were obtained.

SURVEY OF RESULTS

Although the phenomena of the explosions are by now very familiar to most of those to whom this report will come, the following details are placed on record for use in future studies of the data. Bomb A was dropped from a B-29 plane and detonated 518 ft above the surface at $22^h\ 00^m\ 34 \pm 5^s$ on 30 June 46 GCT and date. At the surface the temperature was 30° C, the pressure 1012.2 millibars, and the relative humidity 68%. The wind was 11 knots from 145° (True). The initial explosion quickly grew to a ball of fire which was clearly in view for 2 sec. It was then obscured by the condensation cloud. This began to thin after 4 sec and was completely gone after 15 sec. The cloud rose to 13,000 ft during the first minute; after 7 min the top was stationary at an altitude of 40,000 ft. The cloud could be identified visually for about one hour after the explosion.

Bomb B was suspended from LSM-60 at a depth of 90 ft below the surface, and was detonated at $21^h\ 34^m\ 59.7^s$ on 24 July 46 GCT and date, when the surface temperature was 30° C, the pressure 1011.8 millibars, and the relative humidity 73%. The wind was 7 knots from 135° (True).

The first visual indication of the Bomb B explosion was white water on both sides of LSM-60. A dome began to rise at the rate of approximately 11,000 ft/sec. When it was about 400 ft high, bright jets of flame burst through the top. They lasted about 35 milliseconds. After 0.14 sec, when the dome height was 570 ft a dark colored smoke, through which flames glowed, was noticeable at the top of the dome. After 0.35 sec the smoke formed a well-defined ball of 500 ft radius and a white stem 500 ft higher. By 0.89 sec ball and stem had merged to a white-based black-topped cone, the jagged top having a radius of approximately 970 ft and a height of 2,400 ft. At 0.9 sec the condensation cloud began to form as a skirt about midway up the cone. The horizontal radius of the cloud grew with approximately acoustic velocity; it spread more slowly vertically to form a convex upper surface and a flat, sharply defined horizontal lower surface. At 0.13 sec a second ring of condensation cloud began to form below the first, and at 0.14 sec still a third ring of cloud began to expand radially and upward from the surface of the water. By 2.0 sec these clouds had merged completely. At 3.5 sec the condensation cloud, still expanding radially, began to thin near the base end; at 4.5 sec a vertical column of water could be clearly seen. At 7 sec the condensation cloud was still expanding radially but thinning, leaving the water column unobscured.

The column probably contained less than 500,000 tons of water. It is believed that most of this water was present as a suspension of fine drops in a hollow cylinder roughly 300 ft thick extending from 700 to 1000 ft. The density of this suspension was about six times the density of air, and by 10-12 sec the entire mass of water and air in the cylindrical shell of the column had commenced to subside at a velocity which ultimately reached more than 75 mi an hour. As the suspension of water and air fell from the column it billowed outward over the target ships as the "base surge". The probable nature and origin of the base surge are discussed in detail in Appendix I, Volume II hereto: "Characteristics of the Base Surge" by Cdr Roger Revelle.

The front of the base surge moved rapidly outward, at first with a velocity in excess of 60 mi an hour. The velocity decreased linearly with increasing radius. At the same time the volume of the base surge cloud rapidly increased and the density decreased both through fall-out of water and through dilution with large quantities of air. When the leading edge was 1600 ft from the explosion center the density of the cloud was four times that of air and the dynamic pressure of the moving suspension was equivalent to that from a 120 mi an hour wind. At its greatest extent the base surge extended to 2000 yd in an upwind direction, to about 3000 yd crosswind and to more than 4000 yd downwind. Water continued to fall out of the surge cloud for upward of 20 min. It is estimated that the total fall-out amounted to more than an inch of rain on the target ships and the Lagoon surface. After about four mins the density had decreased to such an extent through fall-out of water that the cloud lifted several hundred yards above the surface of the Lagoon.

Water also fell from the cauliflower cloud, but although this cloud was most impressive in appearance, it probably contained little water in comparison to that in the base surge and it did not extend over as large an area in any direction.

Throughout its entire extent, the base surge contained enormous quantities of radioactive material. Owing to fall-out, dilution, and radioactive decay, the intensity of radiation from the surge cloud decreased approximately inversely as the 3.5 power of the time, so that after 10 min the radioactivity in the cloud was probably not lethal.

Of first importance to the interpretation of the varied phenomena of Operation Crossroads was the construction of accurate tables giving ship and burst locations, and ship headings at the time of detonations. Photographs taken seconds before the detonations from towers on the islands were interpreted to determine the exact positions of certain readily identifiable ships, including SARATOGA, NAGATO, and PRINZ EUGEN, by triangulation. Aerial photographs taken seconds before the detonation in both Test A and Test B, were interpreted to determine the positions of other ships relative to these, and to ascertain the relative bearing of the burst from all ships. It is believed that the bow positions are all correct within 20 yd and the headings within 2°. Negatives of Test A taken from Amen and Enyu Islands, so over-exposed that no trace of detail appeared in the first prints, were reprinted on an extremely high contrast film; the outline of the fireball and the horizon were then clearly seen, and the diameter and distance easily measured. Computation of burst height from measurements on these films lead to a value of 518 ft in each case. The probable error is believed to be less than 10 ft. Details of these calculations will be found in enclosure (B) hereto: "Report of Determination of Burst Height, Test Able" by Lt. Cdr. J. K. Debenham and Ens. H. M. Archer. Tables of ship positions are given in enclosure (A), hereto: "Report on Determinations of Ship and Burst Locations" by Dr. E. S. Gilfillan, Jr.

In appraisal of the results of blast, pressure, and shock measurements three enclosures hereto, (C) "Coordinator's Report of Air Blast and Water Shock in Tests ABLE and BAKER", (D) "Reasons for Expecting the

Peak Pressure to Fall off with the Radius Faster than R^{-1}", and "Origin of Second and Higher Pulses" by Dr. W. G. Penney, and (E) "Report on Ship Instrumentation other than Air Blast and Underwater Pressure" by Cdr. C. H. Cerlach, are particularly useful. All will repay the most careful reading. In small compass the theory and results of the diverse types of measurement are brought into mutual relationship.

The philosophy underlying the instrumentation program was that only one parameter of the blast wave need be measured at any point, because the wealth of information provided by model experiments permitted the complete blast wave to be constructed from just one reading of a single instrument. It had been found from measurements on several hundred small explosions that the shape of the pressure-time curve varied in a simple, predictable way with distance and the size of the charge. By simple mathematical processes the net impulse over a given time and the shock and wind velocities could be computed. Conversely, from a simple measurement of peak pressure, positive impulse, duration of the positive phase, or shock velocity, the whole pressure-time curve and related mechanical parameters could be deduced. The correctness of this theory was strikingly demonstrated by the blast, pressure, and shock measurements of Test A and Test B; the confidence which the planners had in it is reflected in the large number of instruments designed to give just one datum per shot. However, an equally basic planning policy was to provide sufficient overlap of instrumental function so that the failure of any particular theory or group of instruments would not leave a gap in the overall technical picture. Instruments to record the complete pressure-time curve were therefore distributed throughout the target array.

In Test A the air blast measurements were made with instruments of familiar type: piezo electric, strain resistor diaphragm, engine indicator, free piston, condenser diaphragm, aluminum foil, ball crusher, and impulse (Hilliar) gauges, as well as new types including collapsing cans, blast pipes, and diaphragm pressure-time instruments. The theory of each of these instruments is sketched in enclosures (C) and (D). The agreement of these diverse types of measurement with the theoretical curves computed by the Los Alamos groups, and the curves fitted by the Bureau of Ordnance to a variety of blast records for TNT explosions is remarkable. It appears to prove that, for distances greater than 250 yd, at least, there is no difference in the blast produced by TNT and by atomic explosives of equal energy release. All the present evidence is that the blast effects produced were the same as would have been expected from an actual charge of approximately 20,000 tons of TNT.

In Test A the peak pressure at the surface of the Lagoon directly below the burst was 2000 psi gauge; at 500 yd, 1000 yd, and 2000 yd horizontal distance from the point directly below the burst the figures were 53 psi gauge, 10.5 psi gauge, and 3.1 psi gauge respectively. The corresponding durations of the positive pressure phase were 0.4 sec, 0.75 sec, and 1.0 sec. The water pressure directly under the explosion was not measured but must have been the same as the air pressure, 2000 psi gauge at the surface, diminishing slighly with increasing depth. The underwater pressure contours show far more detail than were observed in air pressure contours. Away from the center the water pressures were approximately twice the air pressures, the high pressure propagating with less attenuation than in air. At some radii there were two distinct underwater shocks. Doubtless the second shock as well as much of the later detail was due to reflections.

In Test B the air blast was 22 psi gauge at 500 yd, 4.8 psi gauge at 1000 yd, and 2.8 psi gauge at 1500 yd. The duration of the positive pressure pulse at 900 yd was 0.5 sec. The underwater pressures and durations, depending as they do both on radius and depth, are not easy to summarize, and recourse must be had to enclosure (C) for details. Generally speaking, there were two shocks of approximately the same intensity and duration with about one-tenth sec interval between. At mid-depth the peak water pressure at 835 yd was 7000 psi gauge; at 1084 yd, 4400 psi gauge; and at 2060 yd, 1400 psi gauge. Duration of the two pulses at different radii and depths ranged from 0 to 7 milliseconds. In Dr. W. G. Penney's report "Origin of Second and Higher Pulses", enclosure (D) hereto, a theory is given of reflections which accounts in semi-quantitative fashion for the position, intensity, duration and spacing.

Numerous shock-measuring instruments were installed in target vessels. The records are complicated and not yet completely interpreted; but it is a fair statement that in Test A at distances of more than 1000 yd from the burst, shock phenomena were within the range of previous operating experience, except for effects on very light superstructures. In Test B the accelerations at 1050 yd were less than 200 g. The greatest suddenly acquired velocity (Impulsive Velocity) -- at 750 yd -- was 17 ft/sec. This is roughly the threshold of structural response involving a small permanent deflection. For both tests the radius of negligible damage was about 1000 yd.

In enclosure (D) a theory is given from which positions of equal damage on Test B and in atomic explosions at greater depth, can be computed when the pressure in Test B at a depth equal to the draft of the ship is known. The importance of being able to do this should be particularly noted. It is the means whereby the mechanical experience of Operation Crossroads can be translated into tactical doctrine.

The work of the Oceanographic Section is reported by Commander Roger Revelle as enclosure (F), hereto, "Report of the Coordinator of Oceanography". There were three major objectives, (1) to obtain information on currents and diffusion in Bikini lagoon and surrounding ocean waters, in order to estimate the rate of decrease of concentration and the movement of radioactive materials released into the water by bombs, (2) to determine the effects of the explosions on the Lagoon waters, the living organisms, and the geological characteristics of the atoll - this included measurements of the waves and seismic disturbances produced by the bombs, as well as studies of changes in bottom depth and sediments, and destructive or other ecological effects on the flora and fauna, (3) as a natural corollary of the last problem, to carry out an integrated investigation of the natural environment -- in brief to gain as much purely scientific information as possible concerning this little known area, which had never previously been extensively studied by American Scientists. In order to carry out these objectives, the cooperation of Federal scientific agencies such as the Geological Survey, the Coast and Geodetic Survey, the Smithsonian Institution, and the Fish and Wild Life

Service was enlisted, as well as that of several universities and research institutions, and of Navy laboratories. The work of the Oceanographic Section was thus to a high degree a "joint" operation. Biological, geological, and physical oceanographic studies were begun in early March and continued until the end of August.

The general ocean circulation in this part of the Northern Marshalls area was found to set west at one-half to one knot, moving most rapidly along shore lines parelleling its course, and being reduced or reversed in eddy systems leeward of atolls. Currents were largely confined to the upper 300 meters, with little motion below 500 meters. Temperatures and salinities were always found closely correlated, being respectively 27-29° C and 34.5 parts per thousand at the surface, and 3° C and 34.6 parts per thousand at 1500 meters. The primary circulation inside Bikini Lagoon is rotary in a vertical plane, with upwelling in the eastern and sinking in the western end. In the target area, a relatively thin surface layer follows the wind at speeds from 0.2 to 0.5 knots, depending on wind speed, and overlies a thicker and slower moving bottom layer in which the water moves at speeds of about 0.1 knot, approximately in the opposite direction to the current at the surface. Surface currents quickly change with wind velocity but bottom currents respond slowly. Interchange between lagoon and ocean waters takes place over reefs and passes at a relatively slow rate, more than 25 days being required for half the water in the lagoon to be replaced by new water flowing in from the ocean. Vertical mixing takes place relatively rapidly under normal conditions, with the peculiar result that the highest concentration of radioactive material tends to remain near the area of release, and the concentration is diminished primarily by lateral diffusion, current transport being relatively ineffective. Vertical mixing was abnormally low after Test B because of the very light wind conditions and the stabilizing of the water column, so that the rate of decrease of concentration was about as great as it would have been had the currents been much stronger. In general, however, the predicted transport and diffusion of radioactive material agreed well with observations.

The program of measurement of surface water waves in the target area and in shallow water off Bikini Island, using primarily mechanical bottom-pressure recorders, shore recording bottom-mounted hydrophones, echo sounders, and tower and aerial photography was highly successful. Although no instrumental results were obtained in Test B inside 2100 ft, measurements in to about 1100 ft were obtained from tower photographs. The data from this test are particularly complete and should form a satisfactory base for detailed theoretical analysis.

Waves in Test A were very small and consisted, first, of a slight depression on the water surface amounting to about 6 ft near 100 yd, followed by an even smaller rise. In Test B, where the waves were more impressive, the maximum wave height from trough to crest was 94 ft at a distance of 1000 ft from the explosion. Out to 8000 ft the first wave was the highest; average maximum heights decreased inversely with distance out to this range being respectively 47 ft, 24 ft, and 13 ft at distances of 2000 ft, 4000 ft, and 8000 ft. The first wave disturbances to arrive was always a positive crest followed by a trough which on the average descended as far below the still water level as the crest rose above it.

The number of waves measurable with echo sounders or bottom pressure recorders increased from 3 near the explosion to 6 at 12,000 ft, and 14 or more at 22,000 ft. It is believed that the point of maximum wave height was about 700 ft from the target center. The first wave had a velocity of 74 ft/sec in water depths of 170 ft; its "effective wave length" increased linearly with distance from 1800 ft at a distance of 2000 ft from the explosion to 4800 ft at 12,000 ft. The period likewise increased linearly from 24 sec to 64 sec in going from 2000 ft to 12,000 ft. The periods, wave lengths, and velocities of waves after the first one increased slightly with increasing distance from the explosion but were, on the average, 16.5 sec, 1000 ft and 61 ft/sec respectively. In all its characteristics the first wave behaved differently from the succeeding ones. It may be thought of as a long solitary wave generated directly by the explosion and receiving its initial energy from the high-velocity outward motion of the water. Beyond 2000 ft the slope of the surface due to waves was never greater than 1°. Near the target center the surface had a slope of 15° or more and the waves were breaking. Within 10,000 ft the major part of the energy in the wave system was contained in the first five waves and was approximately 3×10^{18} ergs or about 0.5% of the energy in the bomb. Comparison of the results from Test B with extensive series of model studies of explosions in shallow water show that when the depth of the explosion is made proportional to the cube root of the charge weight, all experimental points are very well fitted by the assumption that wave height, in units of charge radius, varies as the fourth root of the charge weight. Theoretical consideration of this scaling law suggests either (1) that big charges have a greater efficiency in producing waves than small charges, or (2) that more of the energy available for wave formation may go into the first wave when the charge weight is large, or (3) that the ratio of wave length to height may decrease with increasing charge weight. The model studies also show that the column diameters in feet, for explosions ranging from 0.35 lb, to 976 lb TNT, are approximately equal to 7.3 $W^{1/3}$. Here W is expressed in pounds. When the waves entered shallow water their height markedly increased, in very good agreement with theory; photographic measurements show that the first breaker at Bikini was 15 ft high at the instant of breaking. Little damage was done by these breakers although some beach erosion occurred.

Careful soundings before and after Test B show that over an area of about 250 yd by 700 yd the bottom was more than 20 ft deeper after the explosion, the maximum difference being about 25 ft. A net volume of 2,200,000 yd^3 was moved by the explosion and marked changes in the character of the bottom sediments took place. These sediments became quite radioactive after the explosion; values of 10 to 50 microcuries per gram (computed back to a time four hours after the explosion) were found over an area more than 2 mi sq. The lower parts of the beaches on Bikini and Amen Islands and the lagoon-ward side of the reef between these islands were also made radioactive by absorption from the water carried by currents and diffusion from the target area to the beach. Relatively high-frequency seismic vibrations (period about 0.35 sec) of fairly large amplitude - 1.9 mm - were observed at Amen Island after Test B. The effective total energy in the seismic disturbance at this distance was a very small fraction of the energy of the bomb, only about 10^{15} ergs. Other seismic data have not yet been analyzed.

No significant effects on marine or land plants or animals resulted directly from the action of the Test A, although some destruction on shore forms and sea birds occured due to the spreading of oil from damaged or sunken vessels. Definite but comparatively minor biological changes occurred after Test B; one of the reasons for the absence of more significant ecological effects was the poverty of the flora and fauna of the lagoon and the inner reefs. The concentration of radioactive materials by algae and their re-concentration by algae-feeding fish may lead to long term changes, which may only be detected, if they occur, by careful re-examination of the area after several months. One of the most clear cut biological changes was a marked bacterial increase in the bottom waters northwest of the target area, counts increasing from 30 per cubic centimeter before the blast to thousands per cubic centimeter a week later. This increase in the numbers of bacteria was accompanied by a lowering of dissolved oxygen content from 0.45 to as little as 0.15 volume per cent over an area of several square miles between the target center and the northern reef, extending westward from Bikini Island to Romuk. At the same time dissolved phosphate concentration increased, indicating oxidation of organic matter by bacteria and the liberation of the previously bound phosphate. These interrelated biochemical and bacterial changes would normally be expected to take place only if large numbers of living animals and plants had been suddenly killed; the stirring up of the bottom sediment may possibly have resulted in suspending enough organic matter and bacteria to account for the effects, but the extremely low organic matter content of the sediments makes this unlikely.

Reef building corals and calcareous algae were killed or entensively damaged in several areas but in most instances this is believed due to pollution by floating oil. In at least one locality, however, it appears probable that calcareous algae making up the outer reef buttresses were killed by radioactive contamination.

Within the target area the noise of snapping shrimp, one of the most characteristic underwater noises in the tropics, was silenced after Test B probably because of the destruction of these animals by the underwater shock. Several scores of fish apparently killed by the shock, were picked up after re-entry and many more undoubtedly sank to the bottom or were eaten by scavengers. Minor damage to grasses and to the Tacca plant occurred on the lagoon side of Bikini Island due to saltwater flooding by the bomb waves. Damage to shore birds and marine invertebrates in the interidal zone was caused by accumulation of floating oils and their residues. Elsewhere snails, clams, and algae appeared fresh and healthy even when collected in areas of as little as one half hour tolerance. Likewise no significant changes in composition or abundance of zooplankton occured, even though plankton hauls were considerably higher in radioactivity than the waters from which they were collected. No significant reduction or change in the relative abundance of reef fishes was detected by the sampling methods employed.

A 50% reduction in the catch of semipelagic fish, particularly dogtooth tuna and black skipjack, took place after Test B, but it is possible that this was part of a general trend occurring over a wide area, as a smaller percentage reduction in the catch of these species had occurred just previously in the Rongerik-Rongelap area, which was used as a statistical control. The number of pelagic fish taken by fishermen (yellow fin tuna and oceanic skipjack) actually increased after Test B.

One of the outstanding examples of the scientific results of Operation Crossroads not directly related to the bomb tests was a seismic refraction survey of Bikini Lagoon, the primary purposes of which was to determine the subsurface structure and constitution of the atoll. Previous geological studies of atolls have yielded only meagre evidence bearing on these questions and the origin of atolls has long been one of the major problems of geology. By determining the travel times of seismic waves from depth charges dropped along intersecting lines across the lagoon, it was demonstrated that three zones of different seismic velocity exist. The uppermost layer, 2000 ft in thickness, appears to be composed of calcareous sediments similar to those now being deposited. Beneath it is a layer of slightly higher velocity, 7000 ft thick, possibly consisting of mixed limestone and volcanic ash, overlying the irregular surface of the igneous rock at a depth of approximately 9000 ft. Since the animals and plants whose skeletons make up the reef and the lagoon sediments can only live in shallow water, it is evident that considerable subsidence had occurred during the formation of the atoll.

The results of experiments on radio and radar transmissions are discussed in enclosure (G), "Summary Report on Electromagnetic Propagation" by Dr. E. W. Thatcher. Most of the experiments gave negative results. The principal efforts were to determine: (1) the attentuation resulting from propagation through the cloud, (2) the radar reflecting properties of the cloud, and (3) the atmospheric electrical disturbances developed by the explosion. Conclusions are: (1) short range (less than 50 mi) propagation suffered attenuation only if the line of propagation passed directly through the cloud. Long range propagation showed no damage in characteristics attributable to the bomb, (2) weak radar echos were observed briefly on X bands from the air burst. Strong echos were obtained in S, X, and K bands from the column thrown up by underwater burst, resulting in temporary obscuration of targets behind the cloud, (3) atmospheric noise was reported on only one receiver operating at maximum sensitivity approximately 16 mi from the air burst.

The spectrum and thermal radiation from the bomb are discussed in enclosure (H), "Summary of Radiometry Measurements of Atom Bomb Test at Bikini in July, 1946" by Dr. E. O. Hulbert. Spectrograms taken from a distance of 18 mi. (sea) from Test A detonation extended from 3,200 A to 8,600 A, the lower linit being set by atmospheric and the upper limit by lens attenuation. Absorption lines of oxygen, hydrogen, iron, sodium, and possibly of calcium and titanium, were observed. The intensity of the continuous emission spectrum, as measured on the photographic plates, had a maximum at 7,000 A and fell off toward the ultraviolet more rapidly than the solar spectrum. As corrected for atmospheric absorption the spectral energy distribution is approximately according to the Planck law, with deviations in the region from 4,000 A to 6,000 A. The total radiation from 3,400 A to 6,000 A at 18 sea mi is 5×10^5 ergs/cm^2.

It is known that in two narrow bands centered at 3,600 A and 9,400 A less than 7% and 2%, respectively, of the toal energy received came during the first millisecond. This was deduced from the non-operation of certain photo-electric relays which would have tripped had the above percentages been exceeded.

Total radiation from the cloud of Bomb A was no more than that due to reflected sunlight.

The total thermal radiation between 3,200 A and 24,000 A was 1.7×10^{21} ergs. The value similarly obtained at the Trinity bomb was 5.7×10^{20} ergs. Converted to tons of TNT these figures are 40,000 tons and 13,000 tons, respectively. It is believed that uncertainties in the correction for atmospheric absorption, which might easily amount to a factor of 5 or more, are reflected in the above figures. The comparison of the brightness of the Trinity and Bikini detonations, depending as it does on two corrections for atmospheric absorption, seems inconclusive.

At a distance of 8.9 sea mi the energy received from the detonation of Bomb B had a maximum of 60 ergs/cm^2 per sec 0.15 sec after initiation of the blast. A total of 14 ergs/cm^2 was received.

Airborne spectroscopes at a slant range of 7.2 sea mi at an altitude of 9,500 ft showed nothing from the Bomb B detonation.

Nuclear radiation in Test A was measured by means of airborne, surface, and submerged ionization tubes, including some recording installations in target ships, by several types of photographic effects, and by absorption of neutrons in sulfur, phosphorous, lithium, sodium, arsenic, and gold. Agreement between tests with various methods at the different atomic bomb explosions, and with the theory, was quite satisfactory. At 1000 yd the total dosages were 1000 R of gamma rays of energies varying from 5 to 1.2 Mev, 3 Mev x 10^9 thermal neutrons per square centimeter, and 8 x 10^8 fast neutrons per square centimeter. The complete neutron spectrum was not determined. There was no measurement of alpha and beta rays at the time of the Test A detonation as these radiations do not penetrate the skin and are of no energetic or tactical importance.

Since the above mentioned coordinator's reports were written the official estimates of the doses of gamma rays, fast neutrons, and slow neutrons just sufficient to kill half the exposed personnel have been revised downward from 600 R to 400 R, corresponding to 1.4 x 10^{11} per square centimeter of fast neutrons and 5 x 10^{11} slow neutrons per square centimeter.

The nuclear radiation from the Bomb A detonation was such that beyond 2200 yd and in the open even mild forms of radiation sickness (delayed nausea and possible vomiting) would not have been produced at this distance. The total gamma dose was 10 R and other nuclear radiation was completely negligible. At ranges between 2200 yd and 1700 yd, where the total dose of gamma radiation ranged from 10 R to 100 R, some exposed personnel would suffer loss of hair, brief sterility and possibly nausea and vomiting. At radii somewhat greater than 1700 yd a goodly proportion of exposed personnel would become temporarily sick in about an hour, but most of them would be able to perform their duties again after several days. At ranges less than 1700 yd some personnel would be permanently incapacitated or would die, and all unprotected personnel would be out of action for a week or more. At a range of 1350 yd about half of the personnel exposed in the open would die within a month. At 1100 yd, where the total gamma dose was 1200 R, all exposed personnel would have died; the effect of other types of nuclear radiation was still negligible.

At 2200 yd even 1 in of steel between personnel and the blast would have been sufficient to prevent radiation sickness, while at 1700 yd, 4 in of steel would have been necessary. At 1350 yd, 6 in of steel protection would have been required to avoid all radiation sickness, but 3 in would have reduced or prevented serious illness and 1 in would have reduced total fatalities from 50% to 5%. At 1100 yd, 7 in would have eliminated radiation sickness, and 4 in would have prevented fatalities. At 750 yd, the greatest radius at which other types of nuclear radiation became physiologically significant, the total dose of gamma radiation was 6000 R, 11 in of steel would have protected against radiation sickness here, and 7 in would have prevented fatalities, although it would not have eliminated some chronic damage.

Since gamma rays were emitted for a appreciable time after the detonation of Bomb A, that is, until after the radioactive cloud had arisen from the surface, the total dose was not received all at once. At ranges greater than 700 yd, 15% would have been obtained in the first tenth of a sec, and 30% in the first half sec, 45% in the first sec, and

99% in the first 10 sec. It is, therefore, possible that prompt evasive action by exposed personnel when they saw the flash would have been effective at certain ranges. For instance, at 1700 yd, taking shelter behind an inch of steel would have reduced the chance of fatality from 50% to 10%. Fast acting mechanical protective shutters could be effective in reducing mortality at even smaller ranges.

At present not enough is known about the distribution of the neutron dose either in velocity or direction to estimate accurately the lethal ranges of neutrons or the shielding required to give protection from them. It appears that neutrons may present a severe hazard out to as far as 1000 yd, and that from 7 in to 12 in of steel would be required for protection from neutrons at 800 yd.

Within the range at which the neutrons are physiologically significant, the neutron dose is obtained so rapidly after the detonation that it would be impossible for personnel to take evasive action in order to avoid their effects. Personnel situated below the water line so that the neutrons would have to penetrate an appreciable thickness of water would obtain considerable protection from the neutrons. Future vessels designed to withstand the effects of atomic bombing might be constructed with a thin protective layer of some element having a high capture cross-section for slow neutrons. Cadmium would appear particularly promising for this purpose, but other substances might also be suitable.

In Test A all but an insignificant fraction of the fission products were carried away by the cloud, whose activity was still detectable after it had moved 70 mi. Measureable but militarily insignificant radioactivity was induced in the lagoon and on target vessels by the neutron flux, On the surface at a distance of 1000 yd nuclear radiation from the Bomb B detonation was not intense during the first 10 sec but became very strong as the fission products were brought down by water falling from the column. Thus, there would have been some time for manned and steaming ships to take evasive action. The largest first-hour dose, 36,300 R was calculated for the GASCONADE at a distance of 750 yd; the second largest, 5,600 R for the PENSACOLA at 500 yd. These had become 22 R and 14 R per day after 5 and 8 days respectively. In general the decay followed a $1/T^{1.3}$ law.

In Test B from 10% to 50% of the fission products and unreacted bomb components remained in the water, where during the first hour the radiation was roughly equivalent to that from several thousand tons of radium. After one hour the intensity just above the surface of the lagoon near the center of the target area was about 480 R per day. Partly due to decay, partly to diffusion, 5 days after Test B there was nowhere an intensity of more than 0.1 R per day at the surface. Vertical diffusion was very slow. Bottom samples collected near the center of the burst showed high activity but this extended downward only a few inches and consisted of loose sand and mud deposited after the blast. It was noted that coral brought up by the blast and deposited as sand on the target vessels was very radioactive.

Casualties to fish by radiation were reported. It was observed that fish and marine life generally concentrate radioactive material, particularly in the gills and digestive tract. Fish were sufficiently radioactive that they could be photographed by simple contact with the film.

"Technical Photography" by Lt. Cdr. J. K. Debenham is enclosure (M) hereto. This describes camera, methods, and administration. The actual results of the photography are all described by other coordinators.

It seems unlikely that the key numerical values given above will be significantly changed by further analysis of the data. There is still, however, a rich harvest of detail to be reaped by further study. The purpose of the concluding paragraphs of this section is to point out the opportunities which exist, such work as is now in progress on them, and the way to further advances to round out and extend our view of Operation Crossroads as a technical achievement.

Further theoretical work on the close-in pressure-time curves of atomic explosions should be done to determine how they may be expected to differ from ordinary explosions. It is understood that the Naval Ordnance Laboratory is undertaking experimental work with different sorts of molecular explosions to throw light on this point.

At Bikini, it was noted that while the damage to massive objects could be understood in terms of hydrostatic pressure, the damage to light objects could be more easily interpreted in terms of wind velocity. It was also noted that two adjacent foil-meters, both at right angles to the line of advance of the shock wave, but one horizontal and the other vertical, did not suffer the same punctures. A theoretical and, perhaps, also experimental investigation of the damage phenomena in terms of angle of attack and of the ratio of object thickness to blast thickness would be profitable.

The outstanding oceanographic questions still remaining concern the "base surge" which rolled out from the base of the column and engulfed the target ships. Although the general nature of this phenomenon is believed to be partly understood on the basis of the considerations given in Appendix I, Volume II hereto, information on the condition under which a base surge will form, on the amount of water in the base surge cloud, the rate of fall-out and the later behavior of the surge is still fragmentary and uncertain. Some of this information might be obtained from model studies, but full scale explosions in shallow water are probably essential for a complete elucidation.

Numerous questions about the column itself need to be answered. In the field the wave motion much more can be had by careful photogrammetry. This work is now being started by the Bureau of Ships at the University of California. Further studies of impulsively generated waves in shallow water are needed. Although the model tests and the Test B detonation, with associated blast phenomena and wave motions, are by far the most comprehensive study of wave motion which has ever been made, they are confined to a single ratio, of explosive depth to total depth of the water. Model studies of the effect of varying this depth would be most useful in planning bomb countermeasures and further tests.

A post Crossroads study of San Francisco harbor has shown a disturbing vulnerability to explosions of the Test B type. It is strongly recommended that model and radioactive tracer studies be made in every large harbor of importance to the United States for the purpose of planning (well in advance of any likely attack), evacuation and decontamination.

Analysis of data bearing on water circulation in the Marshall Islands has only begun. The final results will be of considerable interest from both naval and scientific standpoints.

Although the pelagic fish taken at Bikini were lost when the ship carrying them went aground, thousands of reef fish and other marine organisms exposed to the explosion are being examined by experts in a number of institutions. There is, as yet, no systematic report of results.

Studies of the nuclear radiation effects at Bikini have brought out the need for more exact knowledge of the doses to produce temporary illness, prolonged illness, and death. Knowledge of the spectrum and time distribution of the primary radiations, and the nature and effect of secondary radiations produced by them in masses of metal, to greater precision than we have them now, is needed for design purposes. Some work presently in progress at the University of Rochester on samples exposed at Bikini may be expected to improve our position in this respect.

An expedition of perhaps ten scientists with several fishermen to Bikini, during the summer months, is needed to make comparison with conditions before the experiments and so detect any long time effects of the explosions. Studies of diffusion in the lagoon brought out the great need for a more sensitive method of detecting fission products. A preliminary study indicates that it may be possible to increase the delicacy of the experiments by a factor of ten thousand. This would open the way to extensive studies of water movements in harbors by means of moderate amounts of fission products.

Perhaps the most immediate opportunity for further gains is the detailed study and correlation of phenomena visible in the many existing films, still and moving, from land, air, and target ships.

There is one air view of LSM-60 at the instant of the Test B detonation, from which much detail of the vessel can be made out, even as she goes to pieces. Several of the fast movies show detail as the first broken water engulfs the ARKANSAS and sweeps high over the NAGATO. A target vessel camera closeup of a destroyer shows the heat wave strike the vessel and start it smoking before the arrival of the shock wave. All pictures in which detail of the advancing water-shock-wave can be seen show irregularities which should be correlated with the locations of submerged submarines and coral heads. Because of geometrical complications there is still doubt whether the group velocity of the water shock from Test B was anywhere significantly greater than the acoustic velocity. A few weeks careful work should settle this point. Further study of rate of growth of the radius of the column, times of fall of the column jets and of water from the cloud is desirable as a basis for tactical studies.

Quite unexpectedly, it was found possible to develop satisfactory images on film which had been fogged by more than 1000 R of gamma rays. Details will be found in Enclosure (L) hereto: "Combined Projects Test BAKER II-11, IX-16" by Dr. C. W. Wyckoff and Cdr. K. Shaftan. The theory used by Cdr. Shaftan to accomplish this result is unorthodox and suggests further investigation. A great quantity of fogged but undeveloped film remains for experimental work; it is deteriorating and will be lost unless something is done fairly promptly. The results of studies of this kind will be most useful in planning any future atomic bomb tests.

There are some things still to be done along meterolgical lines.

The probable trajectory of fission products from various altitudes in the cloud needs to be worked out for correlation with observed increases in cosmic ray activity on certain days and places. An investigation should be made to determine whether all the droplets in the Test A cloud came from condensed moisture or whether some salt water was sucked in. We do not yet know why the Test A cloud did not rise as high as expected. A coordinator's report on weather at Bikini should be written. At present all data is in rough form.

Finally, a serious effort to establish convincing energy balances for the different explosions at different times would be worth while. The amount of nuclear energy released in each explosion is known within a few percent. Fifty microseconds after the Bomb A detonation almost all energy was in the form of radiation and high-speed particles. Two-tenths of a second later most of it was apparently in the form of kinetic and potential energy of blast, some had already degraded to heat at low temperature, and a very little had gone into pressure waves in the water. After two seconds most of the energy was in the form of heat at low temperature in air or water. Some was still pushing the cloud upward and some still radiating outward as a shock wave.

In Test B similar phenomena were more complicated and less well understood. Energy balances, as part of a more complete time-and-space narrative of the phenomena than can be written at present, would contribute a great deal to a unified and intellectually satisfying concept of the Tests as a whole. The need for such a clear concept is already being felt and will become important with the passage of time.

EQUIVALENT TONNAGE OF THE BIKINI BOMBS

An important objective of the instrumentation program was the determination of the energy released by the bomb and of its TNT equivalent. Attention was drawn to the description of the bomb's power in terms of the equivalent amount of TNT by President Truman's statement on 6 Aug 45 that the Hiroshima bomb had more power than 20,000 tons of TNT. It is not likely that 20,000 tons of TNT will ever be exploded in a single charge and of course such an explosion would not be equivalent to an atomic explosion in many respects; for example, because of the much greater volume of TNT and the absence of gamma and neutron radiation. Any estimate in terms of TNT equivalent is an extrapolation from the effects of charges of a ton or less and depends on the definition of equivalence used. This rating of the bomb is, however, useful as it is in line with conventional expressions of explosive effect.

The determinations of bomb efficiency are discussed in the individual reports of the instrumentation coordinators. For purpose of comparison they are assembled here. The most unambiguous statement of efficiency is that of the energy released by fission. The collection of samples of the fission products from the explosion permits a determination of the nuclear efficiency. This is defined as the ratio of total number of fissions in the bomb to the number of fissionable atoms originally present. A knowledge of the energy per fission, of the number of atoms present and of the energy released by TNT permits a simple arithmetical calculation of the amount of TNT to release an equal amount of energy. This determination was made from air samples for the Trinity shot (at Alamagordo, New Mexico) and for Test A, and for Test B from water samples. The results in the three cases agreed within the accuracy of experimental determination which was not better than 10%. The average was taken to be 19,000 tons of TNT and it is assumed that the energy was the same for these three bombs.

As has been stated, determinations of explosive efficiency of an atomic bomb from the measurement of physical phenomena depend on a long extrapolation from observed data and on certain assumptions regarding the conditions or positions for which the atomic bomb and the TNT charge produce the same effects. The basis for such assumptions has been discussed by Dr. W. G. Penney in his Coordinator's Report. The results obtained from the various instruments and types of analysis of blast on Test A are in remarkable agreement for all surface measurements and indicate both excellence of measurement and adequacy of the theory of blast wave propagation.

The measured blast is practically indistinguishable from the blast produced by 20 kilotons of TNT at the same height as scaled from all available experimental data. Unless the scaling laws for TNT do not hold (and this is unlikely), this means that the blast produced at a pressure level of say 50 psi and less by an atomic explosion is the same as that produced by TNT for the same energy release. The validity of this statement depends on the validity of the figure for energy release obtained by the radiochemical analysis of water and air samples. This does not agree with the calculated curve in the Handbook for an energy release of 20 kilotons of TNT. It is interesting that this curve when scaled to 21 kilotons makes an almost perfect fit to the data in the observed pressure range from 120 psi to 2 psi. However, such scaling increases the energy release stated in the Handbook from 20 to 35 kilotons which according to the radiochemists is too much. It is believed that the Handbook curve is the likeliest source for the discrepancy since Crossroads measurements appear to have established the equivalence of blast from atomic and molecular explosives for equal energy release. The energy balance might then be somewhat as follows:

	Blast Energy	Light Energy	Neutron Rays
Atomic Explosion	50%	15%	10%
T.N.T.	50%	1%	0%

	Turbulence & Heat
Atomic Explosive	25%
T.N.T.	49%

The measurements from the airborne condenser gauges on the other hand are much more difficult to interpret. These difficulties have been discussed at considerable length by Dr. J.O. Hirschfelder in Appendix II to the report of the Los Alamos Field Group on Air Dropped Condenser Gauges (project II-1). The difficulties are such that the determinations can hardly be considered comparable with the surface blast determinations. These measurements, however, afford the only basis at hand of comparison of Bomb A with the Hiroshima and Nagasaki bombs except for the later British ground-study estimate at Nagasaki. On each of the Japanese detonations, however, only one condenser gauge record was obtained, so that the results do not have too much reliability. They probably indicate, at least, the relative order of size of the three bombs.

As has been pointed out by Dr. W. G. Penney in his Coordinator's Report that little basis exists for determination of the TNT equivalent of an underwater explosion. The results in a shallow water explosion depend on the distance at which measurements are made in a way which is not yet clearly understood. More emphasis must be placed on the nearer results in the hope that they represent approximately a free water pressure. On this assumption an approximate value can be given for the TNT charge to produce equivalent close-in underwater shock. For air blast in Test B a value can be given for the TNT charge on the surface which would produce the same effect. Again information is not available to translate this figure into the underwater charge required. Values were obtained from surface blast measurements and from air dropped condenser gauges. Again it is doubtful that the air dropped condenser gauge value is comparable with the surface measurement.

On the following table the values for equivalent tonnage of the various bombs are collected:

EQUIVALENT TONNAGE OF ATOMIC BOMBS

A BOMB

Method	Parameter Measured	Equivalent Tonnage Kiloton TNT
Strain Diaphragm gauge	Peak Pressure	20
De Juhasz gauge	Duration of positive pulse	20
Aluminum foil gauge	Shock Pressure	21
Blast Pipes	Peak Wind Speed	20
5 gal cans, 50 gal drums	Peak Hydrostatic pressure	20
Chronograph recorders	Shock wave velocity	21
Airborne Condenser gauge	Energy release from remote shock pressure	17
O'Brien Camera	Growth of fireball	21
Radio-Chemistry	Nuclear Energy release	19

B BOMB

Method	Paramenter Measured	Equivalent Tonnage Kilotons TNT
Ball Crusher Gauge	Water Shock	15-20
Radio-Chemistry	Nuclear energy release	19
Foil Gauge	Surface Shock Pressure	4
Strain Diaphragm gauge	Surface Peak Pressure	4
Airborne Condenser gauge	Energy release from remote shock pressure	12
	HIROSHIMA BOMB	
Airborne Condenser gauge	Energy release from remote shock pressure	15
	NAGASAKI BOMB	
Airborne Condenser gauge	Energy release from remote shock pressure	42
Later studies on the ground (British)	Blast effects	20

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TEST "C"

Test C, now cancelled, was to have been an atomic explosion in deep water. In thinking about this phenomena three questions dominate: (1) What detailed information is needed for strategic and tactical planning, (2) to what extent is this information available and what confidence can be placed in it, and (3) how should the test be carried out if it is later desired to do so. An attempt is made here to examine these problems in the light of Operation Crossroads and previous experience.

Certainly, it would be helpful to know the intensity, shape and duration of the pressure pulse at all points down to 2000 ft below the surface as functions of energy of the bomb and of the depth of submersion. In so far as atomic power can be described in TNT equivalents, present extensive knowledge of underwater explosions gives quantitative answers to all these questions. The remarkable agreement between diverse measurements of the power of Bomb A and Bomb B in tons of TNT is reassuring that ordinary explosive theory is applicable. Of all the complicated mechanical phenomena measured in Test A and Test B, none can be interpreted as in conflict with ordinary explosive theory and most agree (within the experimental error) with the values which would have been predicted for an equivalent charge of ordinary explosive. It would seem that we are on firm ground here, but caution is necessary. The mechanical properties of air are far better understood than those of water. Agreement of theory and experiment in Test A, where the maximum pressures in water did not exceed 2000 psi, threw little light on the validity of the same theory of deep water explosions where the pressures through large volumes are very much larger. Test B gives better evidence although the nearest pressure measurement was made at a distance more than four times the depth of the water, and the phenomena were so complimented by reflections as to make interpretation difficult. There are no experiments on the properties of water at the temperature and pressures which would prevail in a deep atomic explosion, nor are the theories thereof at all precise. The position appears to be, then, that it is probable that the pressure, duration, and wave shape produced at points near the surface by a deep water shot can be calculated in advance within a factor of two.

Given pressure, duration, and shape of pulse we are in much better position with respect to radius of damage to any given class of surface ships. For them, the principal difference between small explosions close by and large explosions further off are the plane wave character and longer duration of the pulse in the latter case. The effect of these was thoroughly explored in Test B. The pulse from a deep explosion will actually be shorter than in Test B at points where the two explosions give equal maximum pressures. The effect of a somewhat greater upward component of the shock at the lethal radius remains to be examined, but it seems improbable that any new types of ship damage will be encountered.

It has been established by Test B that, provided no radioactive poisons reach the surface, the only consequence of military interest from deep atomic explosion are those due to pressure and shock. It becomes, then, of the utmost importance to know the minimum depth at which no plume forms for a charge of given power. Dr. W. G. Penney has given a theory (appended hereto), of a rising atomic bubble in water, which discusses this question, but it contains assumptions to which a deep bubble of water vapor does not accurately conform. The only loss of energy considered is that radiated as pressure waves, and the bubble is assumed spherical throughout its life. But cold water condenses water vapor very rapidly, and it can be shown that at the radius where the pressure inside the bubble is 14 psi, a skin of water a few feet thick can absorb all the energy of the bomb with a 50° C rise in temperature. It seems improbable that the bubble will remain even approximately spherical as it rises. One would expect a flattening of the shape and a heavy rain through the bubble from its upper surfaces, which would tend to collapse it. An atomic explosion underwater differs markedly from a molecular one, in that all but an insignificant fraction of the gases produced are readily condensable. In a molecular explosion a considerable volume of gas has to reach the surface, whether in great bubbles or small, while in an atomic explosion this is not necessary.

Dr. W. G. Penney believes it will be possible from further study of the results of Test B and from further ordinary explosive tests in deep water to predict, with a reasonable accuracy, the pressure phenomena of a deep-water atomic shot as functions of position, power, and depth of bomb. For example, he believes it would be possible to estimate, for any depth and power of bomb and any class of ship the distance at which any type of damage found in Test B is to be expected. He also believes it should be possible to estimate the size and height of the water column to be expected.

Clearly it is not vital to hold a deep-water test. The additional information to be gained from it could hardly be of conclusive importance to any future war. But it appears equally clear that a deep water test is in some respects desirable. Test B seems to have shown that the most effective use of the bomb against a surface fleet would be at the depth for maximum plume, or, more accurately, maximum scatter of radioactive poisons. The only light we have on this is Dr. W. G. Penney's theory mentioned above. To determine the best depth, it is necessary to know the life history of an atomic bubble, which can only be found by experiment. Once the Test is made, a theory along the line of that of Dr. W. G. Penney's, modified to agree with the results found, would permit a close approximation to optimum depth without further experiments.

Another argument for the test is the scientific value of the results. Test A and Test B, while richly productive of results of military interest, gave a relatively meager yield of scientific data, mainly because of the proximity of surface or bottom. On the basis of experience already gained, absence of radiological hazard, and greater time available for preparation (which could be more certainly and accurately made), the results of a deep underwater Test would be much easier to interpret.

In the next few paragraphs an attempt will be made to assemble technical factors which have been running through the minds of personnel engaged in planning Test C, for the consideration of other planners, when and if the test is held.

There is a profound difference in the objectives of Test A and Test B, on the one hand and Test C, on the other. In the first two tests a wide variety of only slightly related phenomena - physical, chemical, radiological, mechanical. electrical, physiological - were studied, whereas in the third only three closely related phenomena - the life history of the bubble, the nature of pressure and surface waves radiated from it are of primary interest. The first two Tests resembled daring industrial sallies into unknown fields; the third may approach the scientific ideal of an experiment - one simple enough to understand.

The opinions of several experts as to the best depth are appended hereto. In line with the foregoing it would seem that the criterion for the best depth should be the minimum at which there is less than one chance in ten that radioactive material will be projected into the air. There appears to be little advantage in having water deeper than 2.5 times the depth of the explosion. Reflections from the surface are even more disturbing than those from the bottom.

The great success of Test B on the understanding of damage to ships may make it unnecessary to use target vessels in Test C. So much has been learned from the first two Tests about types of damage to be expected that knowledge of pressure phenomena alone will suffice to give lethal and slight damage radii without further experiments. Thus the main burden of the first two Tests can be eliminated from the third.

The number of instruments in the danger area can also be greatly reduced, perhaps to 50 in the 10 vertical stations. The emphasis should be on getting the right instruments (most exhaustively tested in advance), into the right places.

As to choice of instruments, piezo-electric gauges, low frequency NOL type microphones, the several University of Washington type pressure recorders, ball crusher gauges, Hilliar gauges and one or two types of wave-height measuring instruments should be employed. The emphasis should be on reliability rather than on variety.

The instruments should be suspended in strings from rubber boats or floats which will not be destroyed by the shot. These should be fitted with radar reflectors to aid in finding them after the detonation.

No satisfactory instrument for measuring wave heights for the deep shot exists. The development of suitable instruments is a major problem. Photography may be the answer.

Many of the instrumental arrangements in Test A and Test B were dictated by possible effects of radiation on electronics and photographic material. These efforts will be absent in Test C. Also, with a smaller task unit, absence of tests on electronic equipment at the time of the shot, and the minor role played by aircraft, there will be far less radio interference. It would seem therefore, that about half the instruments should have self-contained photographic records, and half should use telemetering systems.

Each instrument should be placed at a depth to run its entire course before the first reflection arrives. A chart showing contours of time co-ordinates with instrument depth and horizontal distances is appended hereto. It will be seen that there is no advantage in planting ball crusher gauges more than a few feet below the surface. Hilliar gauges should be planted deeper, and University of Washington type recorders deepest of all.

On the basis of experience gained in Test A and Test B it appears that all instruments should be designed to be serviced and sealed before leaving the mainland, or at least in the lagoon, before placing the ships in deep water. No attempt should be made to open the instruments until they return to the mainland, thus eliminating the need for floating laboratories. By many practice drills with small detonations in home waters before-hand, it may be possible to run the Test as a smart military drill, thereby decreasing time - on-station to three or four days. It appears desirable to make the maximum use of Naval officer and enlisted personnel using only a few highly qualified civilians in addition to those who developed the instruments and brought them to the tests.

The deep shot differs from those in shallow water in that only the depth of an instrument below the surface and the slant range need to be known. Azimuth of instruments can be made unimportant. It therefore becomes unnecessary to know the geographical location of the bomb with any precision. Very exact slant ranges to the strings of instruments can be had by having the bomb suspension emit simultatneous sound and radio pulses, and having the instrument stations receive and repeat these by radio to shore stations.

Remote measurements on the sound of the explosion, and if possible of seismographic and radiological effects, should be made. Low frequency microphones laid off distant beaches should be able to detect the sound an hour or more after the explosion.

CONCLUSION

Final evaluation of the success of the instrumentation program of Operation Crossroads will depend on how well the data obtained fulfills the mission set forth in the opening paragraphs of this section: and consequently, on how well the needs of the armed forces are met with essential information for the interpretation of the overall results of the Bikini tests for strategic and tactical purposes. It is possible however, to state the completeness with which the instrumentation program was realized.

In Test A two major failures occurred which affected the instrumental program. The first of these was an error which caused all the timing signals to be about 10 sec late; so that the signals which should have been given -20, -5, and -2 sec before How Hour were actually given at -9, +2, and +5 sec respectively. Consequently, the instruments dependant on the 20 sec signal started late, while those using -5, and -2 sec started after the detonation. As a result the following projects failed to get results: free piston gauges, shock wave velocity cameras, O'Brien and Bowen cameras on Bikini, Fastex cameras on Bikini and Enyu, and the drum spectograph. The cause of this error is discussed in the 013H report on project IV-12. A few other failures were caused by failures of individual timing units, which caused the loss of individual records, but not of whole projects. The losses occasioned, while serious, did not cost the program any vital data. The O'Brien camera on the BARTON was operated manually and obtained satisfactory data of the same type as that sought by the O'Brien and Bowen cameras on Bikini, as well as the fire-ball growth data which was to have been obtained by the Fastax cameras. The shock wave velocity was obtained, but with difficulty from air-borne camera records, while the burst height and location on the high speed camera programs were obtained as described in enclosure (B) from two fixed camera films. Strain gauges and De Juhasz gauges gave good records of pressure-time and pulse duration. Only time-resolution of the visible spectrum was lost entirely, but fortunately considerable data on this point had been obtained at Alamagordo.

The second failure in Test A was the bombing error which led to detonation about 700 yd from the intended Zeropoint. This wide miss cost some data for equipment which had been located to observe distance variation of effects and had not anticipated so large an error. The detonation was almost over the center of a string of sonobuoys planned to telemeter records of shock wave velocity. It also was too far from some underwater pressure tanks near the NEVADA and from instruments on the DD's and APA's. Again, however, because the planning had provided (both by variety and profusion) instruments to measure nearly all effects by several methods, no essential quantities went unmeasured. As pointed out in the Coordinator's report on Blast . d Shock an excellent picture of all effects was obtained.

The shift of wind to the south of the expected and usual direction caused some difficulty. The heading of target vessels not moored bow and stern was radically different from that anticipated in planning. As a result, data from orientometers, foil gauges, and shock velocity equipment suffered to some extent although adequate data were obtained in all cases.

Test B was not troubled by any major errors such as those in Test A. A few instruments and timing box failures occurred, but none were of such a nature as to jeopardize any major part of the program. The greater experience of all technical groups, the perfect operation of the timing signals, and the excellent predictions of the phenomenologists of expected effects, all combined to make the operations almost one of text book perfection. The only difficulties arising of any importance were those of interpretation of data. Much less is known about underwater explosions particularly in shallow water, than about air burst, and interpretation of data is accordingly more difficult.

It is believed that the major objectives of the instrumentation program have been attained. More time for planning or preparation in any practical amount would have improved the program relatively little. Perhaps the major unsolved problem is that of the determination of the amount of energy transferred to ships and structures by such large shocks. This problem certainly demands much more study and could not have been completely solved in any reasonable time before the Tests.

The organization of the Task Force was well adapted to the scientific task assigned. The policies of making the Technical Director a member of the staff of the Commander Joint Task Force ONE and of assigning him relative rank with the Director of Ship Material and the Chief of Staff were vital factors in assuring the instrumentation program a proper status. These policies, together with the priorities in boats and services given the program, and the consideration given civilian scientists in travel accomodations, berthing, and messing facilities assurred the success of the program. Relations between the civilian scientists and service personnel were uniformly excellent. Instances of friction were so rare as to be noteworthy and, in fact, seemed less numerous than could have been expected on an all-civilian or all-service operation of the complexity and urgency of Operation Crossroads.

The caliber of the technical personnel assigned or recruited by the agencies involved in the instrumentation program was outstanding. In training, experience, ability, and enthusiasm, the quality was uniformly excellent and often pre-eminent. The success which the program achieved was due in major part to this high quality of personnel, who required only support and coordination and little supervision or direction. The Technical Director feels confident that this personnel felt almost unanimously that the consideration and treatment received were the best possible within the limitations of a field operation. Joint Task Force ONE should serve as a model for future technical operations and expeditions of the Armed Forces.

ENCLOSURE A

"Ship and Burst Locations"

by

Dr. E. S. Gilfillan, Jr.

Due to the inadequacy of data at the time of writing, Annex A, "Ship and Burst Locations", is in the process of complete revision.

It is anticipated that this will be finished in the near future.

TOP SECRET

ENCLOSURE B

"Determination of Burst Height, Test A"

by

Lt.Cdr. J.K. Debenham

and

Ens. H.M. Archer

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DETERMINATION OF BURST HEIGHT, TEST A

Measurements were made of two photographs exposed at the instant of detonation from Amen and Enyu Islands. They were both taken with tower mounted K-19 aerial cameras using crossed Polaroid filters. The negatives were highly overexposed so that the fireball did not appear in the original prints. Subsequent examination of the negatives revealed the presence of the fireball image. Positive prints were made on extremely high contrast film (kodalith) in order to increase the contrast to a degree necessary for measurement of the image.

While at Bikini, a burst height of 520 ft was obtained from the Amen negative. Since that time the equivalent focal length of the lens has been more accurately determined by the Bureau of Standards. This value of focal length changes the burst height to 518 ft. The burst height obtained from the Enyu is also 518 ft. It is believed the probable error is less than 10 ft.

APPENDIX I

(a) Method of Measurement.

Fig. 1 shows the method of measuring the photographic image. Twenty-seven sets of micro-comparator measurments of B and t were made of the Amen photograph by three different observers and are given in Table 1. Twenty sets of measurements were made of the Enyu photograph by two observers; these are given in Table 2.

Measurements showed the disc to be circular, so: $c=\frac{1}{2}(b+t)$ if the fireball is near the optical axis. In the case of the Amen photograph the film was removed from the comparator between the seventh and eighth sets of measurements: this explains the sudden change in scale readings.

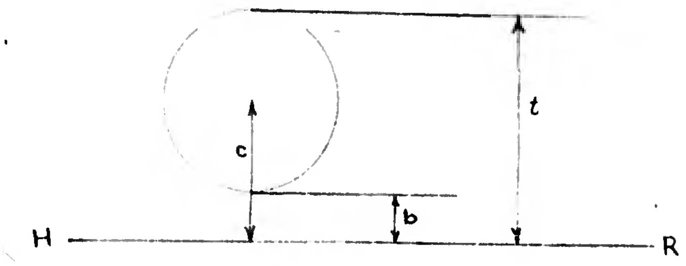


Fig. 1

HR = Horizon.
t = distance upper limit to horizon.
b = distance lower limit to horizon.
c = distance center to horizon.

(b) Derivation of Formula:

The geometry of the problem is shown in Figure 2. The line EC is in the focal plane of the camera. EC is also in the same plane as the line BG. The line BG is in the object plane. The object plane and the focal plane of the camera are parallel, if the film lies in a plane normal to the optical axis. This has been assumed to be true. A small deviation from this condition introduces a negligible error.

The known dimensions are as follows:

f = AC = focal length of camera.
y = EC = focal plane distance between Horizon and Optical axis.
c = ED = focal plane distance between center of burst and Horizon.
D = JM = distance measured on earth's surface from tower to foot of actual burst (published).
AW = distance to horizon (Using 85 ft as vertical height from lens to water surface) = 64,400 ft (calculated BOWDITCH).

Other symbols are:

FX = B

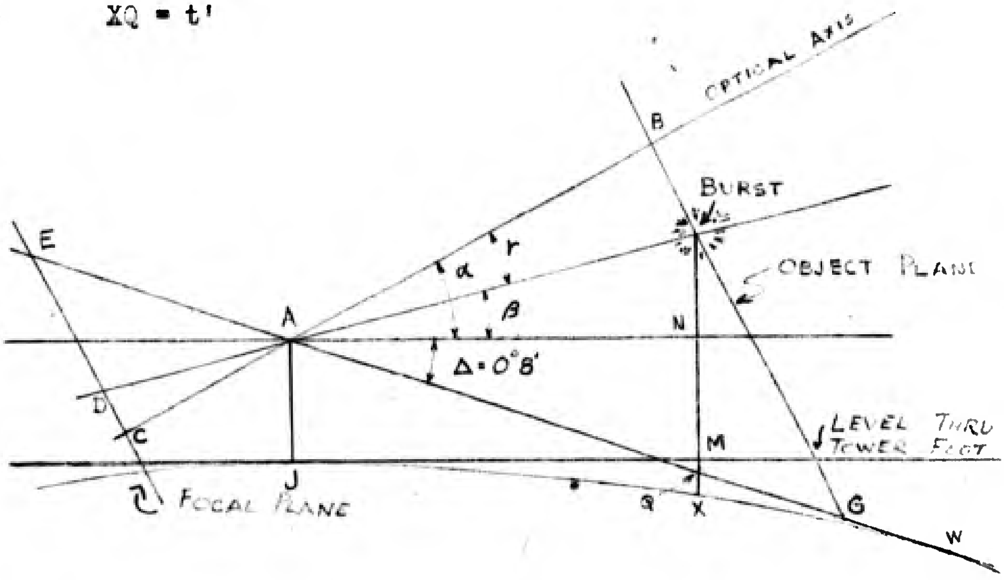
AB = F

FG = C

FQ = t

AF = F'

XQ = t'



Derivation of the expression used to calculate burst height is as follows:

(1) Burst height $= FX = B = t + t'$

t' is the intercept distance on FX between the foot of the burst and the intersection of AW and FX. t' in the case of the Amen photograph is 9 ft, and is 22.5 ft for the Enyu photograph (from BOWDITCH Tables).

Consider:

(2) $\frac{c}{C} = \frac{f}{F}$

(3) $F = F' \cos \gamma$

(4) $F' = \frac{D}{\cos \beta}$

(5) Therefore, $F = \frac{D \cos \gamma}{\cos \beta}$

(6) Also, $C = t/\cos \alpha$

Making the indicated substitutions:

(7) $$\frac{c}{\frac{t}{\cos \alpha}} = \frac{f}{\frac{D \cos \gamma}{\cos \beta}}$$

Solving for t:

(8) $$t = \frac{c \; D \; \cos \gamma \; \cos \alpha}{f \cos \beta}$$

(9) Then from (1), $$B = t + t' = \frac{c \; D \; \cos \gamma \cos \alpha}{f \cos \beta} + t'$$

(C) Calculations:

Numerical values are as follows:

(A) Amen photograph

$f =$ 12.168 in. (BuStandards Calibration).

$c =$ 0.1425 in. (See Table I).

$D =$ 44,200 ft (Test Able Plot Ser. 0004, 8b issue 15 July 46).

$$\mathrm{Cos}\,\alpha = \mathrm{Cos}\left[\left(\mathrm{Tan}^{-1}\frac{Y}{f}\right) - 8'\right] = \mathrm{Cos}\left[\left(\tan^{-1}\frac{1.693}{12.168}\right) - 8'\right]$$

$$\mathrm{Cos}\ 7^\circ\ 49' = 0.99071$$

$$\mathrm{Cos}\,\gamma = \mathrm{Cos}\left(\tan^{-1}\frac{\overline{DD}}{f}\right) \qquad \overline{CD} = \overline{EC} - \overline{ED}$$

$$= \mathrm{Cos}\left(\tan^{-1}\frac{1.505}{12.168}\right) = \qquad = y - c = 1.693 - 0.1425$$

$$= \mathrm{Cos}\left(\tan^{-1} 0.12368\right) \qquad = 1.5505$$

$$\mathrm{Cos}\,\gamma = .99244 \qquad = 7^\circ\ 3'$$

$$\mathrm{Sin}\ (\beta + 8') = \frac{c\ \mathrm{Cos}\,\gamma}{\frac{f}{\mathrm{Cos}\,\gamma}} = \frac{c\ \mathrm{Cos}^2}{f} = \frac{0.1425 \times (0.99244)^2}{12.168}$$

$$\beta + 8' = 0^\circ 40', \beta = 32', \cos\beta = .99996$$

$$B = \frac{0.1425 \times 44200 \times 0.99244 \times 0.99071}{12.168 \times 0.99996} + 9 = 518 \pm 6 \text{ ft}$$

The derivation of the probable error is shown in Table I.

(2) Enyu Photograph.

f = 306.94 mm (Bureau of Standards Calibration).
c = 4.848 mm (See Table II).
D = 31,340 ft (Test Able Plot Ser. 0004 Reg. 8(b) Issue 15 July 46).

$\overline{CD}$ = 0.075 in. (measured).

$$\mathrm{Cos} = \mathrm{Cos}\left(\tan^{-1}\frac{\overline{CD}}{f}\right) = \mathrm{Cos}\left(\tan^{-1}\frac{0.075 \times 25.4}{306.94}\right)$$

$$= \mathrm{Cos}\left(\tan^{-1} .006206\right)$$

$$\mathrm{Cos}\,\gamma = .99998$$

$$\gamma = 0^\circ 21'$$

$$\mathrm{Cos}\,\alpha = \mathrm{Cos}\left[\left(\tan^{-1}\frac{Y}{f}\right) - 8'\right]$$

$$y = \overline{CE} = \overline{ED} - \overline{CD} = 4.848 \text{ mm} - 0.075 \text{ in.}$$

$$y = 2.94 \text{ mm}$$

$$\mathrm{Cos}\,\alpha = \mathrm{Cos}\left[\left(\tan^{-1}\frac{2.94}{306.94}\right) - 8'\right] = \mathrm{Cos}\left[\left(\tan^{-1} .009578\right) - 8'\right]$$

$$= \cos (33' - 8') = \cos 0^\circ 25'$$

$$\cos\alpha = 0.99997 \quad , \quad \alpha = 0^\circ 25'$$

$$\beta = \alpha + \gamma = 0^\circ 25' + 0^\circ 21' = 0^\circ 46'$$

$$\cos\beta = 0.99991$$

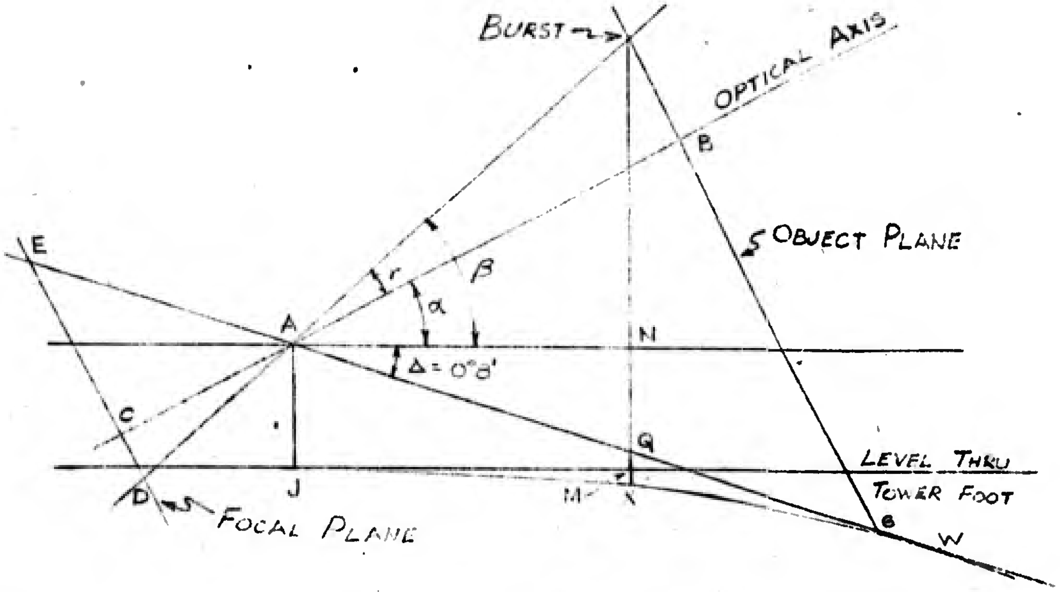
Substitution of numerical values in b(9) using t' = 22.5 from BOWDITCH for burst to horizon distance = 5.45 nautical miles.

$$\beta = \frac{4.848 \times 31340 \times 0.99998 \times 0.99997}{306.94 \times 0.99991} + 22.5$$

Burst Height = 495 + 22.5 = 518 ± 6 ft.

The burst as pictured from Enyu occurred above the optical axis. For this case the geometry of the figure is slightly different than that for the Amen condition for which the burst is pictured below the optical axis. This condition does not change the formula as presented in b(9). The difference in the geometry of the two conditions is shown by a comparison of Figures 2 and 3.

Fig. 3



(d) Tabulated Data:

TABLE I

Micro-Comparator scale readings (inches) - Amen Negative

u	l	h	$\frac{1}{2}(u+l)$	c	$\Delta = \bar{e} - c$ ($x10^{-3}$)	Δ^2 ($x10^{-6}$)
.914	.672	.655	.793	.138	+ 6	36
.915	.676	.648	.796	.148	- 4	16
.914	.676	.650	.795	.145	- 1	1
.913	.676	.650	.794	.144	0	0
.914	.672	.650	.793	.143	+ 1	1
.917	.664	.652	.790	.138	+ 6	36
.915	.671	.651	.793	.142	+ 2	4
.479	.239	.213	.359	.146	- 2	4
.479	.231	[illegible]	.355	.142	+ 2	4
.477	.242	.213	.359	.146	- 2	4
.480	.239	.211	.359	.148	+ 4	16
.476	.236	.213	.355	.142	- 2	4
.480	.234	.214	.357	.143	- 1	1
.478	.240	.213	.359	.146	+ 2	4
.483	.236	.213	.359	.146	+ 2	4
.479	.239	.213	.359	.146	+ 2	4
.478	.241	.213	.359	.146	+ 2	4
.475	.235	.213	.355	.142	- 2	4
.471	.241	.211	.356	.145	+ 1	1
.476	.245	.213	.358	.145	+ 1	1

TABLE I (con't)

Micro-comparator scale readings (inches) - Amen Negative

u	l	h	$\frac{1}{2}(u+l)$	c	$\Delta = \bar{c} - c$ $(x10^{-3})$	Δ^2 $(x10^{-6})$
.473	.239	.212	.356	.144	0	0
.474	.239	.212	.356	.144	0	0
.474	.240	.214	.357	.143	+ 1	1
.475	.236	.214	.356	.142	+ 2	4
.472	.237	.213	.354	.141	+ 3	9
.473	.238	.212	.356	.144	0	0
.472	.238	.213	.355	.142	+ 2	4

$\Sigma\Delta^2 = 1.65 \times 10^{-4}$

$$\sigma = \frac{\sqrt{\Sigma\Delta^2}}{n} = \sqrt{6.11 \times 10^{-6}} = 2.47 \times 10^{-3}$$

Probable Error = .67 = .0017 in.
This corresponds to 6 ft at 44,200 ft.

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TABLE II (Enyu Negative)

u	l	h	$\frac{1}{2}(u+l)$	c	$\Delta = \bar{c} - c$	Δ^2 $(x10^{-4})^2$
96.63	103.52	104.91	100.08	4.83	.02	4
96.60	103.48	104.90	100.04	4.86	-.01	1
96.64	103.50	104.90	100.07	4.83	.02	4
96.63	103.50	104.90	100.06	4.84	.01	1
96.63	103.52	104.93	100.08	4.87	-.02	4
96.60	103.54	104.87	100.07	4.80	.04	16
96.58	103.50	104.91	100.04	4.87	-.02	4

TABLE II

Micro-comparator scale readings (mm)

u	l	h	$\frac{1}{2}(u+l)$	c	$\Delta = \bar{c} - c$	Δ^2 $(x10^{-4})^2$
96.63	103.52	104.91	100.08	4.83	.02	4
96.63	103.50	104.89	100.06	4.83	.02	4
96.63	103.50	104.92	100.06	4.86	-.01	1
96.65	103.50	104.96	100.08	4.86	-.01	1
96.72	103.59	105.00	100.16	4.84	.01	1
96.71	103.50	105.00	100.10	4.90	-.05	25
96.70	103.50	104.95	100.10	4.85	0	0
96.69	103.50	104.95	100.10	4.85	0	0
96.71	103.50	104.96	100.10	4.86	-.01	1
96.71	103.48	104.94	100.09	4.85	0	0
96.72	103.50	104.93	100.11	4.82	.03	9
96.69	103.51	104.93	100.10	4.83	.02	4
96.69	103.48	104.95	100.08	4.87	.02	4

$\bar{c} = 4.848$

$\Sigma\Delta^2 = .0088$

$\sigma = \frac{\sqrt{\Sigma\Delta^2}}{n} = .021$

P.E. = .67 xσ

= .014 mm

This corresponds to ± 1.4 ft.

The probable error has been calculated entirely on the basis of deviations of individual micro-comparator readings from the mean.

(e) **Discussion of Errors:**

The systematic errors introduced are:

(a) Error in determination of the equivalent focal length of the camera lens. An error of 0.1 in. will introduce an error of 3.6 ft in burst height as measured from Amen. The e.f.l.'s of the lenses used were measured accurately by the Bureau of Standards. Error from this source can be safely neglected.

(b) Error in range to burst. An error of 100 ft introduces an error of 1.2 ft in burst height.

(c) Error in measurement of angle α (angle between optical axis and a horizontal plane). An error of 1° in α introduces and error of 2.4 ft in burst height. The error in our determination of α should not exceed 12 min.

(d) Shrinkage of film. This is small and difficult to determine. The distances measured on the film were small so that shrinkage may be safely neglected.

(e) Lack of parallelism of vertical lines from the camera and the burst. These lines form an angle of 8 min and introduce a negligible error.

The effects of atomospheric refraction may be safely neglected for the short light path involved. There should be no systematic change in density of the air from burst point to camera lens.

SECRET

ENCLOSURE C

"Report on Air Blast and Water Shock in Test A and Test B"

by

Dr. W. G. Penney

and

"Photographic Measurements of Shock Pressure"

by

Dr. C. W. Lampson

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Report On Air Blast And Water Shock in Test A and Test B

This report summarizes the essential features of the planning of the air blast and water shock measurements made at Bikini in Test A and Test B. At the time of writing (20 Sept 46) some of the results have not yet been fully interpreted, and many of the records of the underwater shock have not yet been measured. To this extent, therefore, it is not possible to give a complete picture of all the phenomena connected with the blast in the two explosions, but it is thought that when the later results are received from the various groups at present still engaged in making measurements, few changes will be needed except in small points of detail.

The air blast results in Test A show conclusively that the explosion was equivalent in its blast effects to 20,000 tons of TNT exploded at the same point at which the bomb burst. The air blast results over the range of distance 500 yd to 1300 yd in Test B agree well with the air blast which would have been produced by 4000 tons of TNT exploded at ground level over smooth ground. The water shock pulse in Test B shows many peculiar details of fine structure, to be interpreted partly as normal for shallow explosion in deep water, and partly as caused by reflections from the bottom. Because no extensive and reliable model experiments have been made on explosions corresponding with Test B, one cannot make a precise estimate of underwater equivalent of the bomb in terms of TNT. However, sufficient information is known to make it certain that the equivalent blast tonnage was 17,000 ± 3000 tons of TNT.

When more complete results have been obtained by the underwater shock groups, in particular the University of Washington group, it should be possible to make this figure more precise, but the limits stated above certainly cover a range in which the final figure must lie.

Summary of the Planning of the Air Blast Measurements.

Air blast from normal high explosive is usually measured with piezo-electric gauges. Careful consideration was given to the possibility of measuring the air blast in Test A with gauges of this type. Several serious difficulties appeared, of which the chief were the following:

1. A radio remote-control method was required for switching on the amplifiers and taking photographs of the oscilloscope.
2. Photographic film would probably be fogged by gamma radiation.
3. Piezo-electric gauge circuits have high impedance and it was expected that the initial pulse of electro-magnetic radiation associated with early stages of the explosion would cause a heavy signal in the gauge and amplifier circuit and thus mask the record.
4. An elaborate electronic system was required to hold the spot on the oscilloscope screen. If the spot is not on the screen when the pressure arrives at the gauge, of course no record would be obtained.
5. Instead of using an oscilloscope on a ship near the gauge, the alternative method of telemetering the record to a distant ship where manual control of the oscilloscope was possible was considered.

None of the above difficulties were insuperable but in view of the short time available, and of the necessity for using instruments whose performance could be guaranteed, it was considered unwise to rely on piezo-electric gauges as the main instruments for recording the air blast. Perhaps it is worthy of note that if these gauges had been used, the failure of the timing signals might well have resulted in a complete failure to get results.

Several other instruments were considered as offering the possibility of measuring the pressure-time pulse. Among them was the TMB strain resistor diaphragm gauge. This instrument measures the charge of electrical resistance of two wires, one on the inside and the other on the outside of the diaphragm. As the diaphragm deflects, the resistance of the wires increases in a manner directly proportional to the load. Several of these instruments were used by a David Taylor Model Basin group working in the Bureau of Ships team. Amplifiers with photographic recording were tried and proved successful, largely due to the precautions of putting the instruments at least 1200 yd from the bomb burst, and placing the recording apparatus deep in the ship where it was well protected from gamma rays. A more primitive instrument was the De Juhasz gauge which is based on the principle of an engine indicator gauge. The recording device adopted was a simple pen, ink, and paper system. Another instrument from which good results were expected was the free piston gauge, recording the space-time curve of a piston acted on by the side-on or hydrostatic pressure of the blast. The pressure-time curve follows by double differentiation with respect to time.

An ingenious instrument, called the logarithmic time axis recorder and used for measuring the pressure-time record in the water from the Test A explosion, was employed by the University of Washington group, working in the Bureau of Ordnance team. The essence of this device is an elastic diaphragm subjected to external pressure. The diaphragm is damped by means of a sponge rubber pad. As the diaphragm deflects due to external pressure, it carries with it a stylus which records on the flat surface of a dural rod. The rod is set in motion by a spring released by a squib detonated by the arrival of the blast. The effect of the spring is to move the rod against a viscous resistance, given by a silicone fluid, and the space-time curve for the rod may therefore be expressed in terms of exponential functions. By reading the scratch record and interpreting the time base, the pressure-time record for the blast wave is obtained.

Another special instrument for measuring the air blast 8-10 mi away from the burst at elevation 30,000 ft was used by the Los Alamos Group. The instrument is essentially a diaphragm which responds to the air blast. The diaphragm also acts as a condenser in an electronic circuit. Any displacement which the diaphragm suffers changes the frequency of a radio signal which is being emitted by a transmitter carried with the diaphragm on a parachute. The interpretation of the records is difficult, although the records themselves are usually simple. Refraction of the blast wave by winds and the changing air density are complicating factors which introduce uncertainty in the interpretation placed on the records.

Much of the instrumentation finally selected for measuring air blast was purely mechanical, and relied for accuracy on a large number of measurements. The philosophy underlying these instruments was that only one parameter of the blast wave need be measured at any point because the wealth of information provided by model experiments permits the complete blast wave to be constructed from a gauge reading a single parameter. The objection that the blast wave from a normal high explosive and that from an atomic bomb may vary with radius in slightly different ways was not overlooked, but it was felt that the difference between the two would be small. In any case the Bikini tests with their unavoidable uncertainties of the exact location of the ships did not offer the opportunity for a close study of details of this kind.

Single parameter instruments suitable for use were the aluminum foil gauge, the 5 gallon gasoline can, the blast pipes, the ball crusher gauge, and instruments designed to measure shock velocity.

The aluminum foil gauge consists of a sheet of aluminum foil clamped between brass plates in which there are a number of holes of varying diameter. As the blast wave strikes the exposed plate the aluminum foil covering the holes is subjected to load; if the pressure is sufficient, some of the foils covering the holes break. The larger the hole the less the pressure required to burst the foil. By exposing a large number of plates and studying which diaphragms have been burst, it is possible to delimit the peak pressure of the blast. Two geometrical configurations are particularly simple for interpretation. The first is when the blast wave is perpendicular to the foil, and the second is when the blast wave lies parallel to the foil. Because of the impossibility of knowing in advance where Bomb A would detonate, the foil meters could not be placed in position to guarantee that the blast would be either perpendicular or parallel to the foils. An elaborate four-legged structure was designed and made from heavy steel pipes. The legs were welded to the deck, or to any other suitable position on the ship, and on top of this framework of pipes was mounted the foil meter unit. This consisted of 5 sets of circular brass plates each containing its aluminum foils. The bottom and top plates were horizontal and the other 3 were vertical. As a rule, these foil meter towers were placed in an exposed position, and the blast wave which struck them first was free from all reflected pulses from the ship. Experiments made in the shock tube at Princeton University had shown that the foil burst in about 1/4 millisecond, and that if it survived this time, small irregularities in the pressure pulse arriving later did not burst the diaphragm, even though they corresponded with a greater hydrostatic pressure than that of the leading edge of the shock wave. Thus it was felt that the foil meter records would give values of the air blast from the explosion identical with that which would have occurred had the explosion been the same, but all of the ships absent. Considerable scatter in the records was expected, partly due to the nature of the instruments and partly due to the heat from the explosion melting some of the foils, or at least weakening them, before the shock wave arrived. Complicating factors which were successfully overcome were the corrosion of the aluminum by the salt in the air and electrolytic action between the aluminum foil and the brass holder. An extensive series of measurements were made at Princeton to determine the bursting strength of foils of varying thickness when exposed at different angles to the blast wave. These calibrations were employed to interpret the records obtained at Bikini. The exact angle at which the blast struck any particular foil was obtained either from a map of the target ships or from the orientometer records.

The blast pipes were merely pieces of mild steel tube, mounted in a rigid steel holder which was welded on to a suitable rigid support on a ship (such as the stern of a submarine or the top of a gun-turret). Usually five or six pipes were placed within a few feet of each other, the spacing being enough to reduce the interference between their respective air streams to insignificance. The pipes were of different length: the longer the pipe, the more the bending moment at the bottom caused by the wind drag of the blast wave. Thus, if a set of pipes had been ideally located, after the explosion, the set would have had the two longest pipes bent over drastically, one pipe bent very little and the remaining pipes would have been unaffected. By estimating the length that was just critical, the peak shock pressure could be calculated. Whenever possible, the set of pipes was placed on the ship in such a position that the wind to which they were subjected was practically the true free-air wind, i.e. the wind that would have existed had the ship not been there. The very considerable inertia of the pipes ensured that freak variations in the first few feet of the pulse would have no effect.

Thus, in this respect too, the blast pipes employed a different philosophy from that underlying peak pressure instruments such as the foilmeter towers or the ball crusher gauges. These latter have such a short time of response that they react in the first 3 in. of the blast. Provided the first 3 in. were the true "free-air" shock, and had no irregularity due to any cause, the foil or the ball would give a good reading, assuming of course, that a somewhat later freakish reflection off some surface nearby did not introduce a much greater high frequency pressure pulse on the main one, and thus spoil the record.

A simple method of measuring the peak pressure is to observe the crushing of oil drums, gasoline cans or any other empty thin metal vessel with a suitable opening. The blast pressure comes on suddenly, and the resulting pressure on the can causes collapse. The air inside is compressed adiabatically to such a point that the pressure inside is less by a certain amount than the pressure outside, this amount being the maximum pressure difference between outside and inside that the metal case can stand without further yield. Clearly, in the compressive stage, no air must be allowed to rush in through any opening. In the stage where the pressure outside is falling, however, the air must be able to escape from the inside through an opening fast enough to prevent the inside pressure re-inflating the dan, and increasing the volume over its compressed value. Assuming that the observed volume V_2 in the collapsed condition (as observed at leisure after the explosion) is a true register of the collapsed volume in the blast, the over-pressure P_c which caused collapse is

$$P_c = p_o[(V_1/V_2)^{\gamma} - 1] + \Delta p$$

where V_1 is the initial volume, p_o is the atmospheric pressure, Δp is the yield-strength of the can in the collapsed state and γ is the ratio of the specific heats of air.

Instruments designed for measuring the shock wave velocity were of three types, (1) a chronograph recording time intervals between the arrival of the shock at two or more switches operated by the blast, (2) a General Electric recorder camera on Bikini photographing Argon flash bulbs placed on the ships, (3) a line of sono-buoys each carrying a radio transmitter. As the shock struck the buoy, the radio emitted a squeal and this was picked up at the receiving station.

The Argon flash bulb technique was elegant in conception and might have given excellent results if the timing signals had started the General Electric recorder camera at the proper time. However, there was a considerable risk that the flash bulbs would have been triggered by the radiation from the bomb before the arrival of the blast.

Two types of chronographs were used for each detonation, (1) the Aberdeen Chronograph and (2) the spring-driven magnetic wire recorder. The Aberdeen Chronograph had long been a standard instrument for the measurement of projectile velocities, although it had not been widely used for measuring blast velocity. The Spring Chronograph was developed especially for the project.

The Aberdeen Chronograph recorded the intervals between the arrival times of the shockwave at 3 blast switches located in a triangular pattern. By a method of calculation similar to that used in sound ranging it is possible to determine both the direction of the blast with respect to the base lines and the velocity. It was necessary to provide a radio link (the Los Alamos "Black Box") for starting the Aberdeen Chronograph a short time before the explosion.

The Spring Chronograph was triggered by a blast switch, hence it required no radio link for starting. It recorded the time for the shock front to travel from a second to a third blast switch. The base line bounded by the latter two blast switches was almost never directly in line with the bomb, due to the swinging of the ship and uncertainty in the bomb location. Thus it was necessary to know the angle between the base line and the direction of propagation of the blast, as well as the distance and time interval between the switches, in order to obtain the velocity. Reliance was placed principally upon the Optical Orientometers to supply this angle for the detonation of Bomb A, and upon aerial photographs of the ships made at the time of the detonation of Bomb B.

Since the measured velocity was the vector sum of shockwave and wind velocities, it was necessary to make a correction for wind. The velocity of sound was calculated from meteorological data.

Ball crusher gauges were very suitable for measuring the peak pressure on the water in the immediate vicinity of the center of burst. A large number of ball crusher gauges were, therefore, mounted on rectangular logs, and these were moored tightly in position. To help identify the ball crusher positions on the air cover photograph taken just before the explosion, yellow rubber life rafts were attached near to the logs carrying the gauges. While the data provided by these gauges are available, lengthy calculations are involved in interpreting the reading. The details of the reflection of the blast wave at these high pressures at perpendicular or near perpendicular incidence are elaborate and at the time of writing adequate calculations have not yet been made. The ball crusher gauges also suffered from the disadvantage in Test A that their exact position with respect to the center of the explosion cannot be determined better than 20 yd. At the high pressure levels involved, an error of 20 yd in distance from the center is serious. For this reason no great accuracy in estimating equivalent blast tonnage can be expected from the crusher gauge results. Other objections to these gauges, possibly of minor consequence, are:

1. The tilting of the log carrying the gauge may cause the angle of incidence of the blast to be different from that expected.
2. The great heat of the explosion probably vaporizes water over the surface of the sea and log so that, when the blast wave strikes, the first few inches of air near the gauge contain a lot of steam. The time of reaction of the gauge is so short that the presence of this steam may affect the record.

Plans were made for measuring pressure changes in some of the ships. In Test A, for example, the BRULE was left purposely open with her hatch covers removed and most of the doors open. Several types of instruments were used. A large number of 5 gallon gasoline cans were placed throughout the ships of the array. Other special instruments were designed. The most interesting of these was an adaptation of the sensitive element of an altimeter used on "Pibal" weather indicating radio-sonde balloons. The recording system was a stylus and blackened disc driven by a spring and started electrically by the initial motion of the stylus. The altimeter recorder gave time resolution and covered a pressure range from 0 to 10 psi positive and 0 to 5 psi negative. Other instruments used in internal compartments were the pyrex gauges. These consisted of air spaces and water traps that indicated either the maximum positive pressure or the maximum negative pressure.

Summary of the Planning of the Blast Measurements in Test B.

Some air blast was expected in Test B although it was not possible to make any precise predictions. Instruments used were, the foil meter towers, the free piston gauges, the 5 gallon gasoline cans, the TMB strain resister diaphragm gauges, and the De Juhasz gauges.

Most of the instrumentation, of course, was designed to measure the pressure in the water. About 1500 ball crusher gauges were placed in the target area by the Bureau of Ordnance groups. These were mounted in nests of 4 on steel cables running from the bottom of the lagoon to the water surface. About 500 ball crushers were also placed in the water by the Bureau of Ships groups. This time the gauges were mounted near ships with the object of discovering if the pressure in the water near the hull was any different from that in free water.

Hilliar gauges were supported in the water at depths of 21.5 ft and 24.5 ft. These gauges consisted of 7 pistons with different lengths of travel. Each piston acquired momentum by the action of the pressure, and at the end of its travel, struck a small cylinder of copper. The deformation of the copper cylinder enabled the velocity of the piston to be calculated, from the set of readings of any gauge a step-like curve can be constructed representing the pressure-time relationship in the water near the gauge.

An attempt was made to obtain piezo-electric gauge records in the water near the bottom of the lagoon. Gauges were mounted in extremely heavy, robust steel barrels containing the recording equipment. Photographic recording was not attempted. Instead, the signal from the amplifier magnetised a steel strip set in motion prior to the blast by a timing signal. The frequency response of the steel strips was not good, especially above 9 kc and below 50 cycles per sec. However, if the duration of the water blast had been only the acoustical value, the record would have been adequate. Because the duration of the positive pulse was about 3 times greater than the value expected when the planning was being done, the records obtained were not good enough to follow the true pressure-time pulse in the water after about 2 milliseconds. Tests are now being made on the recording system using step functions with the object of improving the interpretations which can be placed on the record.

One of the instruments commonly used for assessing damage from underwater explosions is the pot or diaphragm strain gauge. This consists of a circular copper diaphragm rigidly supported at its edges suspended in the water, with water on one side of the diaphragm and air on the other. The force of the explosion dishes the diaphragm and by measuring the yield at the center and at various radii from the center, it is possible to deduce some facts about the explosion. The instrument does not, in general, record peak pressure, momentum, or energy; the exact interpretation is, in fact, still open to analysis. Because many measurements have been made with these gauges on normal high explosives it was considered desirable to place a number of them in the lagoon in the hope of correlating the measurements with those on normal high explosives.

The University of Washington group attempted to obtain comprehensive records of the underwater pulse in Test B. They used logarithmic time axis recorders to measure the first few milliseconds of the pulse, and backed these up with other instruments similar in principle to obtain the complete record. The modified form of the instruments consisted of an aluminum diaphragm with a silicone baffle system. The diaphragm carried a stylus which recorded the deflection on a circular steel disc coated with a very fine chrome surface. The disc was set in rotation by means of a spring clock mechanism triggered by the time signal. The scratch recorded on the chrome surface is extremely fine and must be examined microscopically in order to discover the details. Each disc needs careful measurement and the results have to be plotted on squared paper, point by point, because the time axis on the disc is circular and direct microscopic photography is unsuitable for presenting and measuring the results.

Some information about the underwater blast can be obtained by high speed photography of the initial motion of the water plume. Arrangements were therefore made to have Fastax cameras and Eastmans at Bikini and Enyu focused on the center and triggered by the timing signal given out two seconds before the explosion. Eastman cameras were also mounted in one of the photographic aircraft.

Air Blast Curves for Interpretation of Test A Results.

For purposes of general discussion, when it is not necessary to define the exact meaning of every scientific term, a useful comparison of the blast wave of an atomic bomb may be had in terms of TNT equivalent. The statement has often been made that the Nagasaki type of atomic bomb is equivalent to 20,000 tons of TNT. When attempts are made to define this statement, one runs into a fog of uncertainty. It would be impossible in a short summary of this type to give a complete statement of the present position; an attempt will be made in a later report to write out all the relevant facts. Readers must however be given a brief description of position, and be warned that as matters stand no absolute significance can be attached to the statement that the blast equivalent of any particular atomic bomb explosion was a certain number of tons of TNT. The only precise statement possible is that the explosion released a certain amount of energy, defined as ergs, calories, number of fissions or any other appropriate units.

The experimental measurements on the blast determine the variation of peak pressure with radius; they also give the duration of the positive phase of the blast and some details of the suction phase. These are the facts; only when an attempt is made to express them in terms of TNT does the trouble begin. As far as the writer is aware, only one set of data on peak pressure versus radius can be regarded as unequivocally definite. This set of data refers to bare charges of TNT exploded in free air. The best measurements are undoubtedly those made at Woods Hole, and they cover a range of peak pressure 3-50 psi.

The assumption has usually been made, and certainly the experimental facts within their limitations support the assumption, that the conventional scaling laws can be applied to predict the blast from one set of explosions to another provided the geometrical shapes are all preserved.

It would be extremely rash, however, to suppose that a charge of 64 lb of TNT (a weight often used in model experiments) detonated in free air and a charge 20,000 tons of TNT detonated in free air would scale one to the other. The visible and ultra-violet radiation in the two cases would not scale in the same way as the blast wave energy, and the energy produced by the burning of the detonation products in the air would not scale. The writer would expect tremendous heat radiation from an explosion of 20,000 tons of TNT, at least the equal of that produced by an atomic bomb. If the two blast waves were known, and the fact that the small charge was 64 lb was known, and an attempt was then made to estimate the weight of the large charge from these data, it is not to be expected that the results would be nearer than 5000 tons to the true figure. Since no measurements have ever been made on 20,000 tons of TNT in free air, the only possibility open to us for calibrating the blast wave from an atomic bomb is to use the results from charges of normal weight. No great loss is caused by adopting this definition. The next point to be raised is much more serious. This refers to the fact that no atomic bomb has yet been detonated in such a manner that the free-air pressures over the range 2-50 psi could be measured. Therefore, to make the desired comparison it is necessary to introduce into the model experiments a nearby reflecting surface (the ground), and then to assume that the scaling laws for the complete system, including the ground, apply to the model charge and to the ground. The facts of the matter are that the scaling laws fail for large ratios of charge weight.

The first approximation that might be tried is to assume that the ground is rigid in the mathematical sense. The explosive wave in the air from a charge at ground level would then be identical with that produced by twice the weight of charge in free air. Comparison with experiments reveals that this is not the case; placing a charge on the ground by no means raises the blast equivalent in terms of a free air charge to twice the value. Moreover, the results from the charge on the ground depend on the nature of the ground, and, it might be anticipated, on the weight of charge. Part of the discrepancy may be due to the presence of the ground affecting the after-burning but the chief reason is cratering. According to experiment, raising a charge above the ground has the effect of increasing the peak pressure and positive impulse at any given radius along the ground, except near to the charge. This increase is partly due to the peculiar non-linear mechanics of shock waves; the particular phenomenon to which reference is now being made is usually called the "Mach Effect". Part of the increase is also due to the fact that the ground acts as a better reflector for the smaller pressures which now come upon it. At no point of detonation above the ground does the pressure pulse behave as if the explosion were on a rigid reflecting surface. Possibly, the wave at infinity does behave in this way, but the statement is debatable.

From what has been said in the above paragraphs, the difficulty involved in predicting accurately the true air-blast from an explosion whose free air characteristics are known should now be apparent. Only by incorporating experimental facts by rule of thumb methods can one get near to the true position. Accuracy better than 10-20% in peak pressure at any given radius is impossible. The converse operation of using a measured blast wave to estimate the weight of charge cannot be performed with certainty better than ± 25% accuracy. Even then, the figure will relate to "weights scaled from charges of the order 64 lb", and will not be the true weight.

Having outlined the position, we shall now proceed to explain how the results from the Bomb A explosion were to be calibrated in terms of tons of TNT equivalent. The method by which ill-definition was to be avoided consisted of constructing pressure-radius curves for various tonnages at various heights. From this point onwards, X tons of TNT is that amount of TNT which would produce the defined blast curve, irrespective of the fact that the real physical tonnage that would do the job might differ from X in either direction by as much as 25-30%.

Part of the data available are the Bureau of Ordnance curves prepared from a study of data from Princeton, Woods Hole and ARD (England), and the theoretical studies of Kirkwood. One may express some confidence in the accuracy of these curves over the range of pressure 3-40 psi since they are mainly experimental, but for greater pressures the curves are entirely theoretical, and in any case apply to the flame zone. One would not expect the high pressure regions to apply to atomic bomb explosions. The other data available to us are to be found in the Los Alamos Crossroads Handbook. The curves given there apply only to an atomic explosion of energy release 20,000 tons TNT, at a height 600 ft above a rigid surface.

In order to bring the Los Alamos curves into the picture, it was decided after discussion with Dr. G. K. Hartmann and Dr. C. W. Lampson that the best procedure was to adopt the Los Alamos curve but to try to modify it to fit the geometrical configuration at which the Test A explosion occurred. It was supposed that the Los Alamos curve could be calibrated for equivalent blast tonnage by fitting it to a Bureau of Ordnance curve at the 7 psi level. When this is done, the Los Alamos curve has a blast equivalent of 12,000 tons, and the height of burst is of course 600 ft. The Los Alamos curve for 20,000 tons blast equivalent obtained in this way agrees fairly well with the Bureau of Ordnance curve. However, it must be remembered that the equivalent height of the Los Alamos curve is now 710 ft. The changes which would result from bringing the height of burst down to 520 ft would be to increase the pressure a little at 100 psi, to make no change at 70 psi, and to add about 0.1 or 0.15 psi in the pressure range 70-3 psi.

Underwater Blast Curves for Interpretation of Baker Results.

The magnitude of the underwater blast produced by an atomic bomb is of cardinal importance. Purely theoretical speculations are difficult to make, largely because the equation of state of water at enormous pressures and high temperatures is unknown. All that could be said before the second Bikini experiment about the equivalent tonnage of an atomic bomb underwater was that no scientific reason had been discovered for expecting the equivalent tonnage in water to be very different from that in air.

The geometry of the Test B explosion was unlike that normally adopted in underwater explosion work. Effectively, Bomb B was placed at a depth of two charge radii while the water was only four charge radii deep. A few model experiments at the Taylor Model Basin had shown that the peak pressure would fall off with radius much faster than it would have done in deep water. To some extent the loss in peak pressure would be compensated by a much greater duration of the pulse. Mathematical calculations for a blast equivalent of 20,000 tons of TNT indicated that very approximately the peak pressure at radius R ft would be given in psi by values shown in Table I. The pressures which would have been expected at the same distance in deep water are given in the line denoted by P_f while the surface value of peak pressure expected at Bikini is given by P_s.

Table 1. Expected free-water pressure P_f, and surface pressure P_s psi

R	330	600	800	1000	1500	2000	2500
P_f	20,000	10,600	7650	5890	3710	2650	2070
P_s	12,700	6080	4250	3200	1970	1390	1070

The duration of the first pulse expected at depth G ft at a radius where the surface pressure was p psi is given by the formula -

$$\tau = 1.4 \times 10^{-3} a p^{1/2} \text{ milliseconds} \qquad (2)$$

Results of Air Blast Test A

Although the failure of the timing signals and the large error in placing the bomb caused a serious loss of results from instruments measuring air blast, sufficient data were obtained to permit the pressure-radius curve at the water surface to be defined at least with 5% accuracy at all points except in the circle of about 100 yd radius immediately below the bomb. Very few records giving positive duration of the blast were obtained, but fortunately 8 TMB gauges gave excellent records, showing a positive duration of about 0.9 sec at the 5 psi level. The foil gauges also gave consistent results, although there is still an unresolved variation between the foils which were side-on and horizontal and those which were side-on and vertical.

The results are summarized in Table 2. The last column gives the equivalent blast tonnage based on the Bureau of Ordnance curve for 20,000 tons at 520 ft and also on the Los Alamos curve scaled up by the methods described earlier. It is most important to realise that the tonnage figures have no absolute significance. It will be seen that all measurements except the ball crushers are in close agreement, and when the results are interpreted in the manner described, the equivalent blast tonnage is 20,000. Further work is certainly needed before any final interpretation can be attached to the readings of the ball crusher gauges although it appears that they indicate a lower tonnage than the other methods. No results have yet been presented on the airborne condenser gauges.

Table 2. Summary of Results on Equivalent Blast Tonnage of Bomb A.

Method	Blast parameters Measured	Peak Pressure Range	Reliability	Equivalent Blast Tonnage (kilotons TNT)
TMB De Juhasz	Peak Pressure Positive duration (0.9 secs)	3-8	Good	20 20
Aluminum foil gauges	Shock pressure	2-10	Very good	21
Blast pipes	Peak wind speed	10-100	Fairly good	20
5 Gallon Cans 55 Gallon Drums	Peak hydrostatic pressure	3-35	Very good	20
Chronograph Recorders	Shock Wave Velocity	3-20	Very good	21
Ball Crusher	Shock Pressure	600-1500	Do not know how to interpret results at present.	
Air-born condenser gauges	Peak Pressure & duration at 30,000 ft alt.	0-0.2	Difficult to Interpret	7.4

Some of the above instruments may have been affected by the structure on which they were mounted. For example, the TMB gauge on APA BRISCOE showed that the pressure in the blast wave at first increased beyond the initial shock pressure. No doubt this effect is real and representing diffraction of the blast wave around the ship leading to an increase of pressure in the vicinity of the gauge. Similarly, one set of blast pipes on ARKANSAS show a greatly enhanced wind speed. These pipes were mounted on a gun turret aft and the blast struck first the ship and then the gun turret and then spilled over onto the blast pipes.

One of the most accurate measurements made on the air blast came from the chronograph recorders on ARDC-13. The instruments gave the average velocity of the shock wave from one vertical wall of the dock to the other. It is not clear that the shock would travel over the dock at the same speed that it would have done if the dock were not there. The wall on which the shock first impinged would send out a diffracted wave at first of considerable intensity. This wave would follow the initial shock but the details of the geometrical shape of the waves are not very well understood. Certainly, the blast must have diffracted down into the stall of the dock and one would expect this effect to be accompanied by a decrease in shock pressure at the level of the top of the wall across the dock. A model experiment in a blast tube should be made to test whether the measurements can be used to give the free air shock velocity. It is not expected that much correction will be necessary but the work is worth doing because the measurements have excellent precision.

A summary of the peak shock pressure at various horizontal distances from the centre of burst is given in Table 3. Some uncertainty still remains in locating the exact centre of burst, but the values given in the table are only slightly changed if the assumed centre of burst is moved 50 ft.

Table 3. Peak pressure of air blast in Test A as a function of horizontal distance

Radius R yd	0	360	500	600	750	1000	1200	1400	1600	2000
Peak Pressure P psi	2000	100	53	34	21	11.0	7.8	5.5	4.5	3.0

The shape of the pressure time curve at various radii may be constructed from the formula

$$p(t) = P(1-t/T_o)e^{-t/T_o}$$

where P is the initial shock pressure in psi, t is the time in seconds which the pressure p(t) is desired, and T_o is a time in seconds which varies with radius in the following way:

Table 4. Positive Duration of Air Blast in Test A

R yd	360	500	750	1000	2000
T_o sec	0.42	0.46	0.59	0.75	1.0

The above formula for p(t) is not valid for radii less than 750 yd beyond the point at which p(t) falls to zero (i.e. beyond time T_o sec). However, for radii greater than 750 yd, the formula gives a fair representation of the whole pressure-time curve including the suction phase.

The positive pressure and the suction developed in internal compartments of various ships gave some good results. The adapted altimeter recorder indicated 1.8 psi positive at 0.2 sec, 0 at 0.87 sec negative, 0.7 sec at 1.7 sec and 0 again at 3.5 sec in the compart.D-109 (crew's quarters) of ARKANSAS. Similar values, but rather less in magnitude, were recorded in the No. 1 fireroom of NEW YORK and in the forward engine room of SALT LAKE CITY. These and other results obtained deserve further study especially from the point of view of Naval Constructors.

The results obtained with the pyrex maximum and minimum manometers showed similar effects but in the case of these instruments the writer, at least, is doubtful of the validity of the readings. Until the instrument has been properly tested in a pressure chamber simulating pressure established in the ships' interiors, no confidence can be placed in the readings. The time of the response of the instrument and kinetic effects of the moving water will probably be found to affect the readings considerably, and the results therefore probably have only qualitative significance.

The results from the 5 gallon cans gave a series of good readings, especially on BRULE. This ship was purposely left open, and 5 psi was reached in number 2 hold. Other positions in the ship reached 2.5 - 3 psi. Records from a large number of internal compartments of ships showed that the pressures never reached 2.5 psi. On the whole, therefore, the air blast did not penetrate closed compartments.

Results on Blast from Test B.

Good records were obtained with the foil meters, the TMB strain gauges on BRISCOE and the 5 gallon cans. No evidence, of course, on the air blast inside the water column was obtained, but over the range of distance 550 yd to 1500 yd the data are good enough to give a peak pressure vs radius curve which is accurate within 10%. The results over this range are equal to those which would be produced by 4000 tons of TNT exploded on the water surface. Table 5 gives values of peak pressure in psi vs radius.

Table 5. Air Blast Results Test B: Peak Pressure vs Radius

R yd	550	650	800	1000	1200	1500
P psi	16	9.6	6.6	4.8	3.8	2.8

The TMB gauges on BRISCOE at 900 yd indicated a peak pressure 6 psi with a positive duration of 0.50 sec. These results agree very well with a 4000 ton explosion.

The vertical stations of ball crusher gauges gave a most comprehensive picture of the maximum pressure in the water at all depths over the range of distance 835 ft to 5000 ft. The peak pressure at various levels in the water at any one station show remarkable fluctuations with depth and for the most part these variations must be caused by irregular reflections from the bottom. However, the results do indicate that at 835 ft distance the maximum pressure of the surface of the water is only 4600 psi while it rose to 7000 psi at 70 ft and deeper. Similarly at 920 ft the pressure at the surface was only 4000 psi rising to 6000 psi at a depth of 80 ft. Further from the center, the difference between the pressure at the surface and that deeper in the water was proportionately much less, and at a radius 3000 ft or more, the maximum pressure was approximately the same at all depths. Table 6 summarizes ball crusher readings on the maximum pressure at mid-depth denoted by p_m, and the maximum pressure at the surface of the water, donated by p_s.

Table 6. Ball Crusher Results Maximum Pressure at Mid-Depth and at Surface.

R ft	835	928	996	1084	1278	1554	2060	3040	3700	5000
p_m	7000	5900	5200	4400	3200	2300	1400	800	560	330
p_s	4600	4200	3800	3800	3000	2200	1400	800	560	330

The Hilliar gauges gave satisfactory records. They appear to indicate that the pressure remained approximately constant for about 1/2 millisecond at the value given by the ball crusher gauges and that the pressure then decayed to zero at a time of the order one to two milliseconds. None of the Hilliar gauges gave a reading after about one millisecond but the downward slant of the pressure-time curve is good enough to give some indication of the trend of the curve towards zero. It is not possible to give any exact comparison of the durations with the theoretical formula mentioned earlier although it may be said that the agreement appears to be good.

Three good piezo-electric records were obtained. Two of them were at 2400 ft from the centre and 1 at 3000 ft from the centre. As explained earlier, the recording system was a magnetic steel strip and the frequency response was not good enough to trust the record after about 1.5 milliseconds from the initial shock. Therefore, further work is necessary before it will be possible to construct the true shape of the pressure-time curve after 2 milliseconds. The records show a large negative phase following the initial rise and lasting for 5 milliseconds at which time the trace is again quiescent. This effect is certainly not real and is due to the imperfections of the recording system.

All 3 records show that the first signal to arrive at the gauge was a ground shock beginning about 1 millisecond before the primary water shock. The gauge on the bottom at 2400 ft showed a peak pressure reading of 1100 psi and the duration of the pulse was 5-7 milliseconds. At about 7 milliseconds the water appeared to be undisturbed, but at 22 milliseconds a second positive pulse arrived practically identical with the first.

At radius 2400 ft and 50 ft above the bottom (i.e. at depth 100 ft) the initial pulse was distinctly weaker than that recorded by the other gauge on the bottom. The peak pressure was only of the order 600 psi and the duration was 2-3 milliseconds. No second pulse was observed.

At radius 3000 ft from the centre and 50 ft above the bottom, only one pulse was observed with a peak pressure 530 psi lasting from 2-3 milliseconds.

The University of Washington group obtained a large series of records most of which have not yet been analysed. Their results are in close agreement with those obtained with ball crushers and with piezo-electric gauges, details of which are summarized above. The most remarkable feature of the University of Washington records is the long interval between the first and second pulse during which the gauge records zero absolute pressure. At the moment, it is not clear whether the water near the gauge during this interval was cavitated or whether it was completely undisturbed. The former of these possibilities is the more likely, because if the water was still and undisturbed the gauge should have read the static head, whereas in fact it read zero. There is no doubt that valuable information and new knowledge will result from an analysis of the University of Washington records but at this time it is not possible to give any details.

Valuable records were obtained from ball crusher gauges placed on or near the hulls of ships. Once again, a final analysis has still to be made but a preliminary survey shows pronounced diffraction defects. For example, the pressure near the hull of a ship on the side remote from the burst was often only 40% of that on the exposed side. Some of the gauges were attached to cables suspended from outriggers projecting from the ship, and the depths of these gauges were 2 ft, 4 ft, 6 ft, and 8 ft below the water surface. Results on these gauges are interesting and they appear to show that in the first 8 ft, peak pressure increases from a value almost zero to a value agreeing fairly well with that measured at the same distance at the vertical ball crusher stations described earlier. In the opinion of the writer, these results are misleading. The reason why the gauges recorded such low pressures was that the pressure pulse lasted less than the response time of the instrument. To illustrate these remarks with one example - at a distance 800 yd the pressures recorded by the ball crushers at depth 2 ft, 4 ft, 6 ft, and 8 ft were 420, 600, 770, and 870 psi respectively. These figures suggest that they are tending to a limit of about 1000 psi. According to theory, the pressure pulse at depth 8 ft corresponding with the shock pressure 1000 psi is about 350 microseconds. This is about the same as the response time of the gauge. Thus a pressure of 1000 psi at all depths less than about 8 ft will not record the true pressure because the instrument has not reached its proper deflection before the pressure is released.

Photography of the Test B detonation by fast cameras has revealed an extraordinary sequence of events which occurred in the earlier stages. One of the most successful films was obtained with an Eastman camera running at 800 frame/sec with good timing signals, taken from the air at low altitudes. The leading edge of the water shock can be seen running over the surface from the center and it is followed by a series of other pulses apparently not much weaker than the first. Triangular jagged patches show in the flickering of the water surface and the probable explanation of these is that reflection is occuring from some coral head on the bottom. The air shock follows later and the boundary of the water shock is clearly defined by the white spray which is being thrown into the air. Measurements are now being made of the velocity of expansion of the water shock over the surface and of the rate of expansion of the air shock over the surface. These measurements can probably be used to deduce the peak shock pressure in the water and in the air as functions of radius. In the case of the water shock, the velocity will very quickly be practically that of sound in water so that in this case probably only the first 300 yd from the center will give results of significance.

When a shock wave in water strikes normally on the free surface, the surface suddenly acquires a velocity which can be measured by suitable high speed photography. If it were not for the fact that the water surface under these conditions is unstable, an excellent value of the pressure at the shock front could be deduced from the value of the initial velocity. However, any such value suffers from the disadvantage that the value obtained must be too high, but the excess over the proper value cannot be computed. Nevertheless, plans were made to measure the initial stages of the upward movement of the water surface in Test B by means of high speed photography. The results were most successful: the initial velocity for the first few milliseconds was of the order 5000 ft/sec, falling to 3500 ft/sec at 10 milliseconds. If it were not for the instability of the surface, an explosion of 20,000 tons of TNT at depth 90 ft would have given an upward velocity of 2900 ft/sec. As expected, the measured value was appreciably higher.

Model experiments on high explosive charges had indicated that the explosion of 20,000 tons would give a water spout 2400 ft in diameter. The observed diameter was not as great as the predicted value; the actual observed diameter was about 1860 ft. It is not generally realized what a remarkable phenomenon the plume is. The theory of sound fails completely to provide an explanation. According to the theory of sound, the free surface moves vertically upwards all the way out to infinity, and there is no indication whatever of a sharp demarkation between the column and the practically unmoved water just outside. Nor does the assumption of a tensile strength for water much improve the position. The proper explanation is probably to be sought on the lines of the Meyer solution - the plume is that region where the Meyer solution fails and an unstable regime, involving a rarefaction from the surface, is prevailing. Once the shock front near the water surface is reduced to its stable angle of incidence a more normal acoustic theory becomes applicable. Further work along these lines is necessary in order to understand the mechanics of the plume. It is perhaps worthy of note that the water in the plume only comes from the surface layers. If it came from deep down it is unlikely that the near-in ball crusher stations would have remained in situ. Statements made that the amount of water thrown into the air was between one and ten million tons should be treated with skepticism. In the outer region of the plume probably only a few feet of water were thrown upwards.

The height expected for the plume assuming that the bomb behaved like 20,000 tons of TNT was about 7000 - 8000 ft. This is a good deal less than would be indicated by model experiments if the height observed for these was scaled up in the ratio of the cube root of the charge weight. The reason for the discrepancy is that gravity makes a big difference to the height to which the water is thrown by a large explosion whereas for a small one, the effect of gravity is entirely subsidiary to that of air resistance. The observed height of the plume was 5100 ft. This is less than the expected value, perhaps for two reasons; the first being that plumes are always irregular in their behaviour and the second that the atomic bomb causes a pressure wave in the first hundred feet rather different from that caused by 20,000 tons of TNT.

One cannot at present give close limits to the equivalent underwater blast tonnage of the Bomb B. The ball crusher vertical station at 835 ft shows that the pressure in the water at this distance reached 7000 psi, corresponding with an equivalent tonnage of 15,000. If any measurements had been obtained nearer than this, the indicated tonnage might have been slightly greater. The close agreement of the ball crusher readings at 835 ft with the expected form of pressure distribution with depth in the water and the expected type of variation is so good that one may express confidence that the ball crushers which read 7000 psi at depth 60 ft or more were actually recording the true free water pressure. One may therefore say that the equivalent tonnage was at least 15,000 and might have been 20,000.

Photographic Measurements of Shock Pressure. (by Dr. C. W. Lampson)

Certain valuable information concerning the blast pressures at close in distances from the bomb was obtained from the measurement of motion pictures taken from an Army air plane in Test A. The pictures were taken from an oblique angle with a Mitchell Camera at approximately 96 frame/sec.

The primary data were the positions as a function of time of the intersection of the fire ball with the surface of the water, and at larger distances the intersection of the blast wave with the water surface. The line of intersection of the blast wave could be determined quite accurately as the edge of an area of froth or foam on the water caused by the high wind velocity behind the shock front. This line of foam is very clearly defined in the photographs. The plane being at an angle of approximately 7° from the horizontal it was possible to obtain a distance scale from the height of the center of the fire ball above the water while the time scale was provided by the nominal speed of the camera.

It was necessary to differentiate the time distance graph when finally obtained to determine the velocity of the blast wave. In the pressure region below about 500 psi the relation between the shock wave velocity u and the peak blast pressure P is given by the equation

$$P = \frac{7}{6} P_o \left[\left(\frac{u}{a} \right)^2 - 1 \right] \qquad 3)$$

where P_o equals the atmosphere pressure and "a" is the velocity of sound in air at the local conditions of temperature and humidity.

The results of these measurements of shock pressure are given in Figure 14. The points fit the Los Alamos computed curve exactly up to a pressure of about 100 psi. The shape of the curve drawn through the measured points above this pressure level is interesting in that it apparently shows a systematic departure from the computed curve and in an unexpected direction. The actual bomb detonation point being appreciably lower than the height for which the curve was computed, one would expect that the actual pressures would be higher since the same horizontal distances are actually closer radially to the bomb. The velocity distance curve shows an abrupt discontinuity at a horizontal distance of 200 yd. This occurs at the approximate distance that represents the radius of formation of the Mach wave at the water surface and also the maximum excursion of the fire ball. Velocity distance data exist at distances down to 100 yd from the bomb foot, but the fact that regular reflection occurs in this region makes it impossible to use the simple equation given above which depends for its validity on the existence of a Mach wave at the water surface. Adequate calculations have not at the moment of writing been made which will allow these velocities to be converted to pressures.

Figure 15 shows the same points plotted on a smaller scale together with the pressure data given by the foilmeters. The Los Alamos curve scaled up to 21 kilotons is passed through the assemblage of points showing the remarkable agreement between the two sets of data and with the shape of the theoretical curve up to 100 psi. Above this pressure the general position of the points is not in agreement with the Los Alamos curve but diverges in the direction of lower pressures.

There is no doubt that this film which is identified by Navy number 18377 (PSL) and by Army number 32 I - 21 - 1, gives valuable data in the regions which suffered blast pressures so great as to destroy any equipment designed, for the direct measurement of the blast.

Results from Air Dropped Condenser Gauges. (by Dr. C. W. Lampson)

A series of 4 records were obtained on both Test A and Test B from the air dropped condenser gauges at an altitude of approximately 27,000 ft. In Test A one gauge developed air leakage so that its impulse reading was lost, but all gave values of peak pressure. The data are presented below.

Air Dropped Condenser Gauge Data (Test A)

Channel	R	Ps(±10%)	T (±3%)	I (±10%)
17	41,200	.168	1.59	.126
18	41,200	.178	1.62	.141
3	43,800	.143 ±20%	-	-
13	43,800	.150	1.61	.116

The records obtained on B Day were taken at an altitude of approximately 24,000 ft.

Air Dropped Condenser Gauge Data (Test B)

Channel	R	Ps(±10%)	T (±3%)	I (±10%)
1	42,500	.122	1.20	.070
5	42,500	.136	1.25	.082
7	42,500	.128	1.34	.085
16	42,400	.110	-	-

In this data R is the slant range, Ps is peak blast pressure in psi, T is the duration of the positive phase in seconds and I is the positive impulse in lb sec/in.^{2}.

The data seems to be fairly consistent but the interpretation in terms of tonnage is very obscure because of difficulties in making the altitude corrections and because a reliable pressure distance curve extending to large distances is not available for either normal explosions or atomic bombs. There is also a discrepancy between the distances indicated by radars and those computed from the elapsed time.

The average value of the equivalent amount of TNT that would have produced the same blast in Test A, computed by Hirshfelder using Fuchs second order correction for altitude is (1) 7.4 kilotons from peak pressure (2) 11.2 kilotons from impulse and (3) 8.5 kilotons from blast energy. He computes the equivalent nuclear tonnage to be (1) 17 kilotons (2) 21.7 kilotons and (3) 15 kilotons from the same considerations. The discrepancy between these values and the average value of 20 kilotons TNT blast equivalent found by numerous methods of measurements on the surface indicate that the problems of correction for the effects of altitude, variable temperatures, and humidity have not been solved.

In Test B Hirshfelder's calculations for the equivalent TNT tonnage are (1) 5 kilotons from peak pressure (2) 6.4 kilotons from impulse and (3) 5.2 kilotons from blast energy. The nuclear tonnages from the same considerations were computed to be (1) 11.7 kilotons (2) 12.7 kilotons and (3) 9.1 kilotons. The correspondence between the TNT blast tonnages from the condenser gauge values and those found by measurements near the surface is somewhat better in this case possibly because the atmospheric conditions were different.

It may be concluded from the condenser gauge results that the interpretation of these records into blast tonnages is very difficult and that either the theory needs to be considerably amended and extended or that much more meteorological data is necessary over that taken before reliable values of tonnage can be computed from their readings.

Since the radio chemistry determinations of the bomb efficiency in Test A gave approximately 20 kilotons TNT energy released, and the blast pressure and impulse measurements near the surface gave approximately the same value for equivalent TNT blast tonnage; it would appear that the mechanical effects from the release of a like amount of energy is the same for normal explosives and for atomic bombs. The ratio between nuclear TNT tonnage and blast TNT tonnage would then be one. This seems reasonable and if true would resolve a well argued question concerning the addition of different forms of energy emitted from the atomic bomb.

A Description of the Figures Illustrating the Main Results on the Air Blast and Water Shock in Test A and Test B.

Fig. 1 - Shows the results from the aluminum foil meter units for the air blast in Test A. Circles denote readings which are the average of the two horizontal sets of foils. Crosses represent the vertical sets of foils. The two curves are those for 20,000 tons of TNT detonated at height 520 ft; one curve is that predicted by the Bureau of Ordnance and the other is that scaled up by methods described in the text from the Los Alamos 20,000 ton energy release explosion at height 600 ft.

Fig. 2 - Shows the results from the blast pipes, 5 gallon cans, 55 gallon drums, and the beer can giving the pressure at various radii from the center. The two curves are the same as those shown in Fig. 1.

Fig. 3 - Shows results from the TMB gauges and the De Juhasz gauges in Test A. The two curves are the same as those in Fig. 1. The

durations of the positive pressure measured by these instruments are in excellent agreement with those expected from a 20,000 ton explosion.

Fig. 4 - The best estimate that can be made of the shape of the pressure-time records at various levels of pressure. The units of the vertical ordinate are those of the maximum pressure and the units of time are T_0 values of which are given in the text for the various pressure levels. Only the positive part of the curve has significance if the peak pressure exceeds about 10 psi but for lesser pressures, the suction phase is also fairly well represented.

Fig. 5 - The foil meter results in the air blast in Test B. The theoretical curve corresponds with 5000 tons TNT exploded in the air.

Fig. 6 - The air blast in Test B as recorded by the blast pipes and 5 gallon cans. The curve corresponds with 4000 tons of TNT exploded at the water surface.

Fig. 7 - The TMB record obtained on BRISCOE (distance 900 yd) in Test B. The record agrees closely with that expected from 4000 tons of TNT exploded at the surface.

Fig. 8 - The ball crusher results from the vertical stations. The results at 835 ft, 928 ft, 996 ft and 1084 ft all show a decrease of pressure as the surface is approached. The irregularities are probably caused by freak local reflections from irregularities on the bottom. It is considered that the 7000

psi value recorded at 835 ft at depth 60 - 90 ft is very close to, if not identical with, the free water values. The equivalent tonnage for these readings is 15,000.

Fig. 9 - The ball crusher results at shallow depths. It is considered that these records do not establish that the pressure near the surface did not reach the full value established further down; rather, the peak pressure was the same but the duration was too short for the gauge to give a true reading.

Fig. 10 - A Hilliar gauge record obtained at depth 20 ft, 1090 ft from the center. The trend of the curve indicates that the positive duration was about 1.6 milliseconds compared with an acoustical 0.76 milliseconds and a value 2.1 milliseconds predicted by the Meyer corner solution (formula 2).

Fig. 11 - A piezo-electro-magnetic strip recorder record obtained at the bottom 2400 ft from the center. The gauge shows a second pulse arriving 22 milliseconds after the first and a quiescent period between the two pulses. There is another disturbance occurring about 40 milliseconds after the second one.

Fig. 12 - The equivalent underwater blast tonnage from the ball crusher vertical stations calibrating the tonnage solely in terms of recorded peak pressure. It will be noticed that the near in stations indicated 15,000 tons whereas the stations at 5000 ft indicated only 1000 tons. The drop in tonnage as estimated in this way is to be expected; the true tonnage is approximately 15,000 - 20,000 tons.

Fig. 13 - The rate of rise of the plume in the early stages.

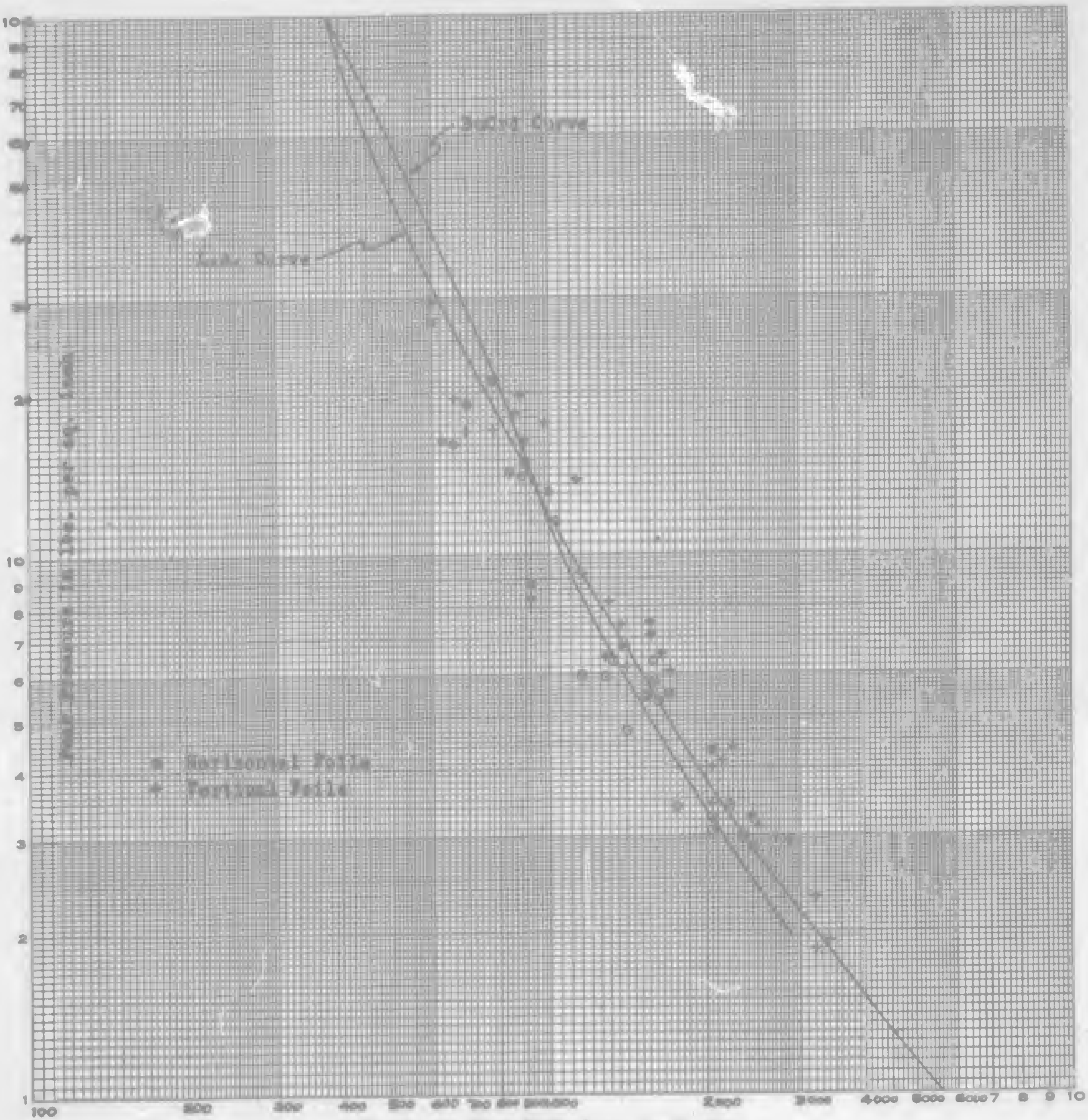
Fig. 14 - This shows the peak blast pressure as a function of distance determined from aerial motion pictures showing the fire ball, and the intersection of the blast wave with the water surface.

Fig. 15 - This shows the above data together with the foil meter data. The agreement between the two sets and with the theoretical Los Alamos curve in the pressure region below 100 psi is noteworthy.

Shot Able

Peak Air Blast Pressures from Foilmeters

(After Lampson)

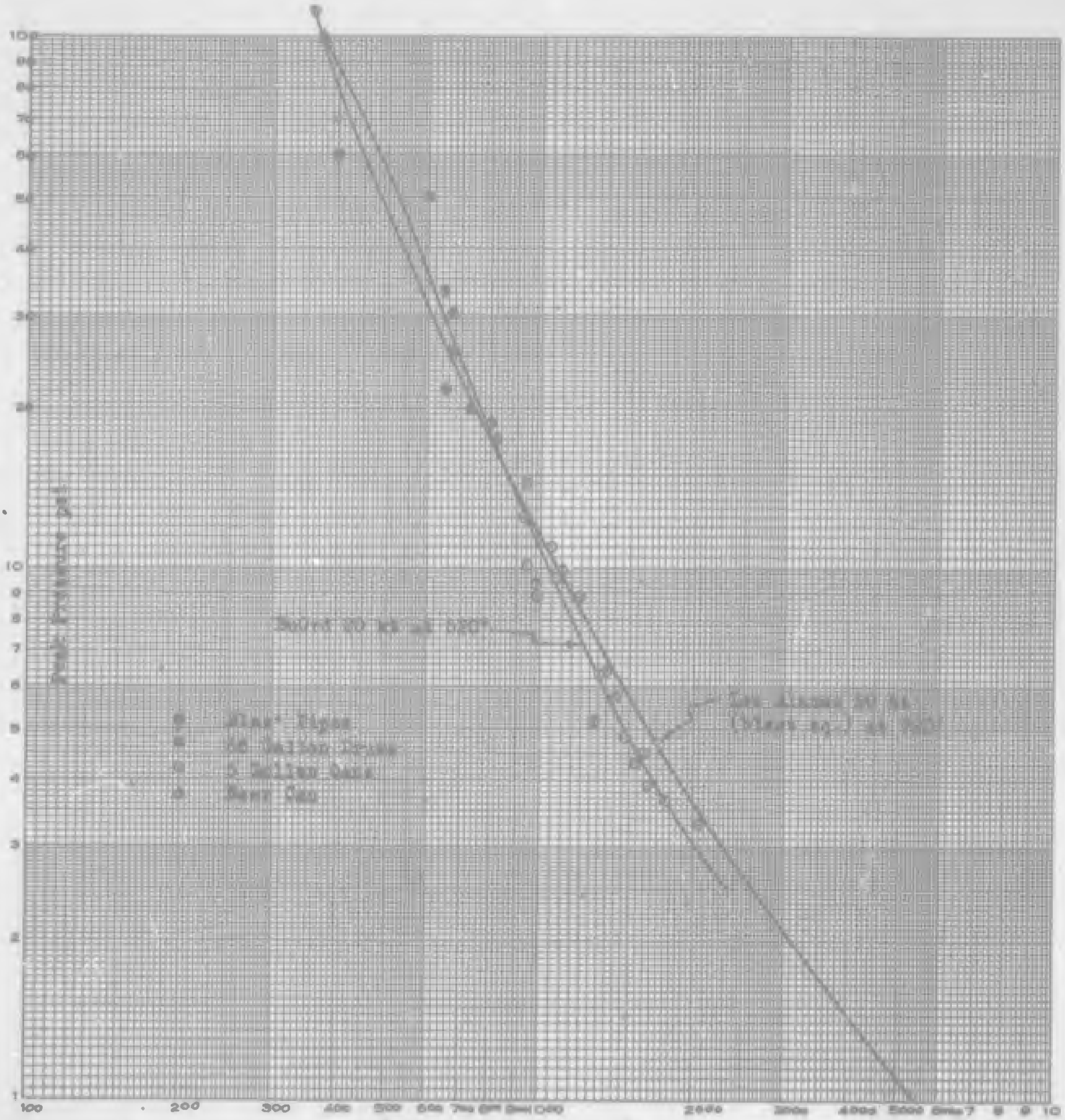


Distance from Bomb Foot in Yards

Figure 1

SECRET

Air Blast - Test Able



Horizontal Radius in Yards

Figure 2

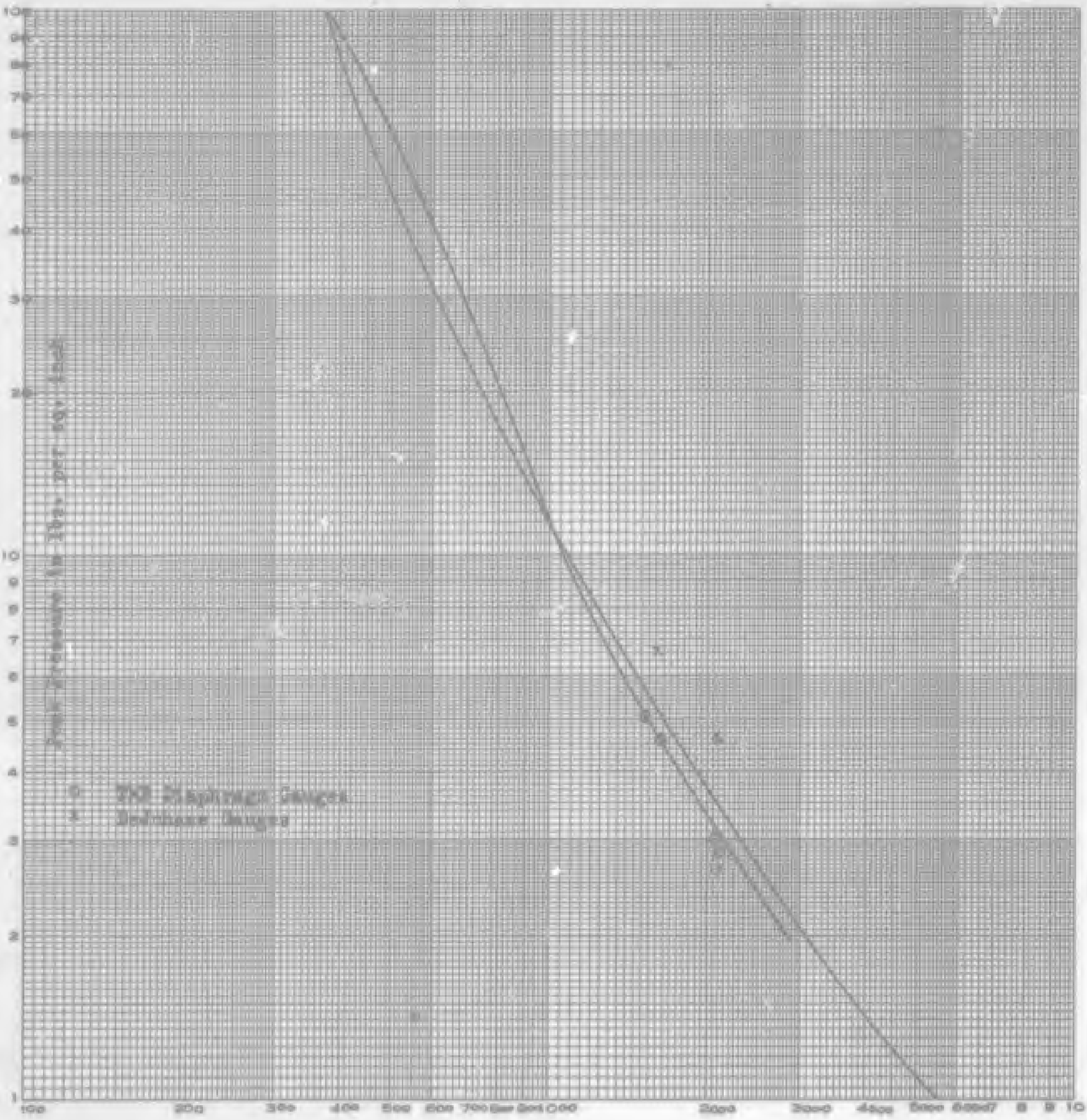
SECRET

Shot Able

Peak Air Blast Pressure from TMB

Diaphragm and DeJuhase Gauges

(After Tamarkin)



Distance from Bomb Foot in Yards

Figure 3

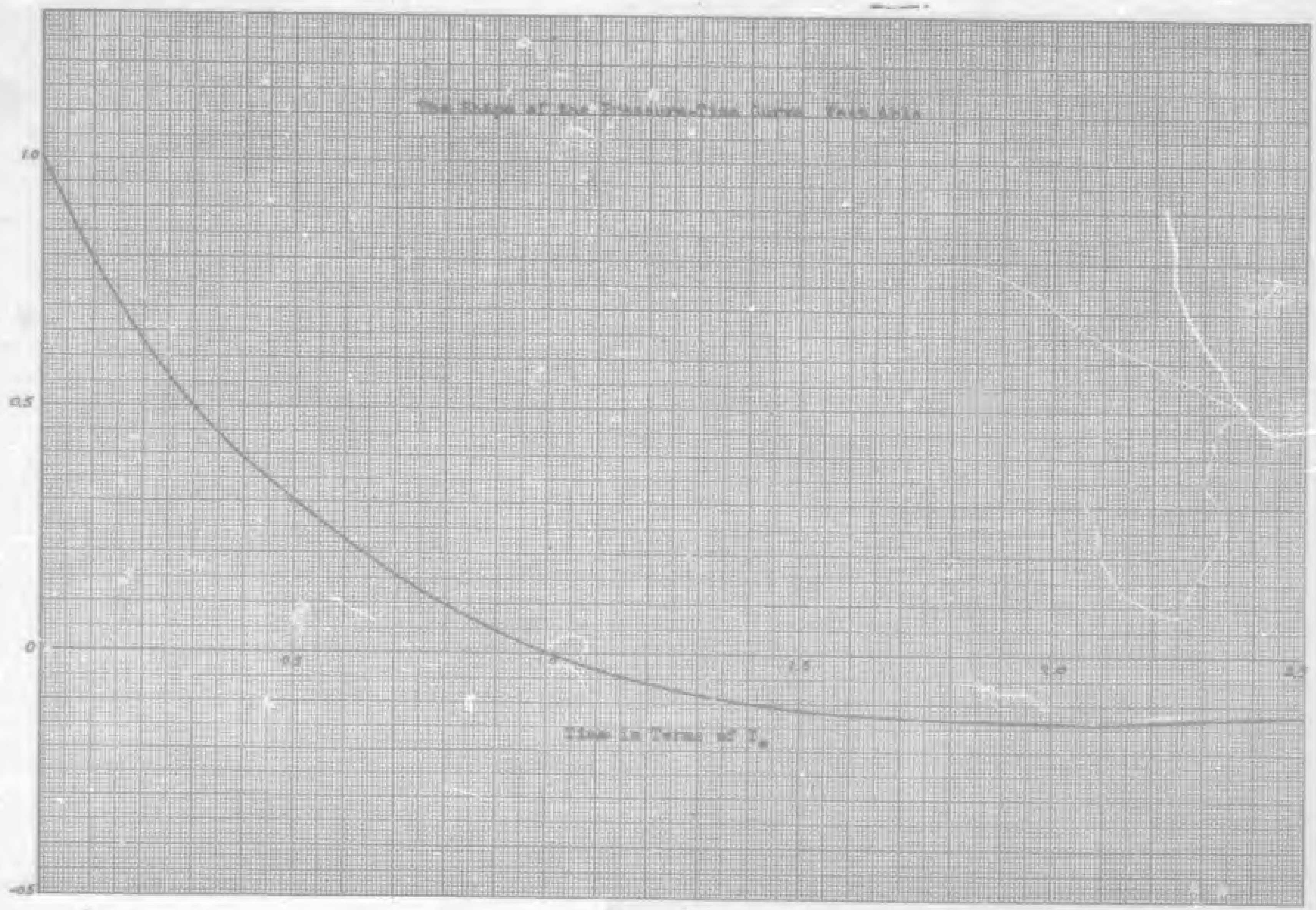

The Shape of the Pressure-Time Curve Near Axis
1.0
0.5
0
-0.5
0.5
1
1.5
2.0
2.5
Time in Terms of T_e

Figure 4

Shot Baker

Peak Air Blast Pressures from Foilmeters

(After Lampson)

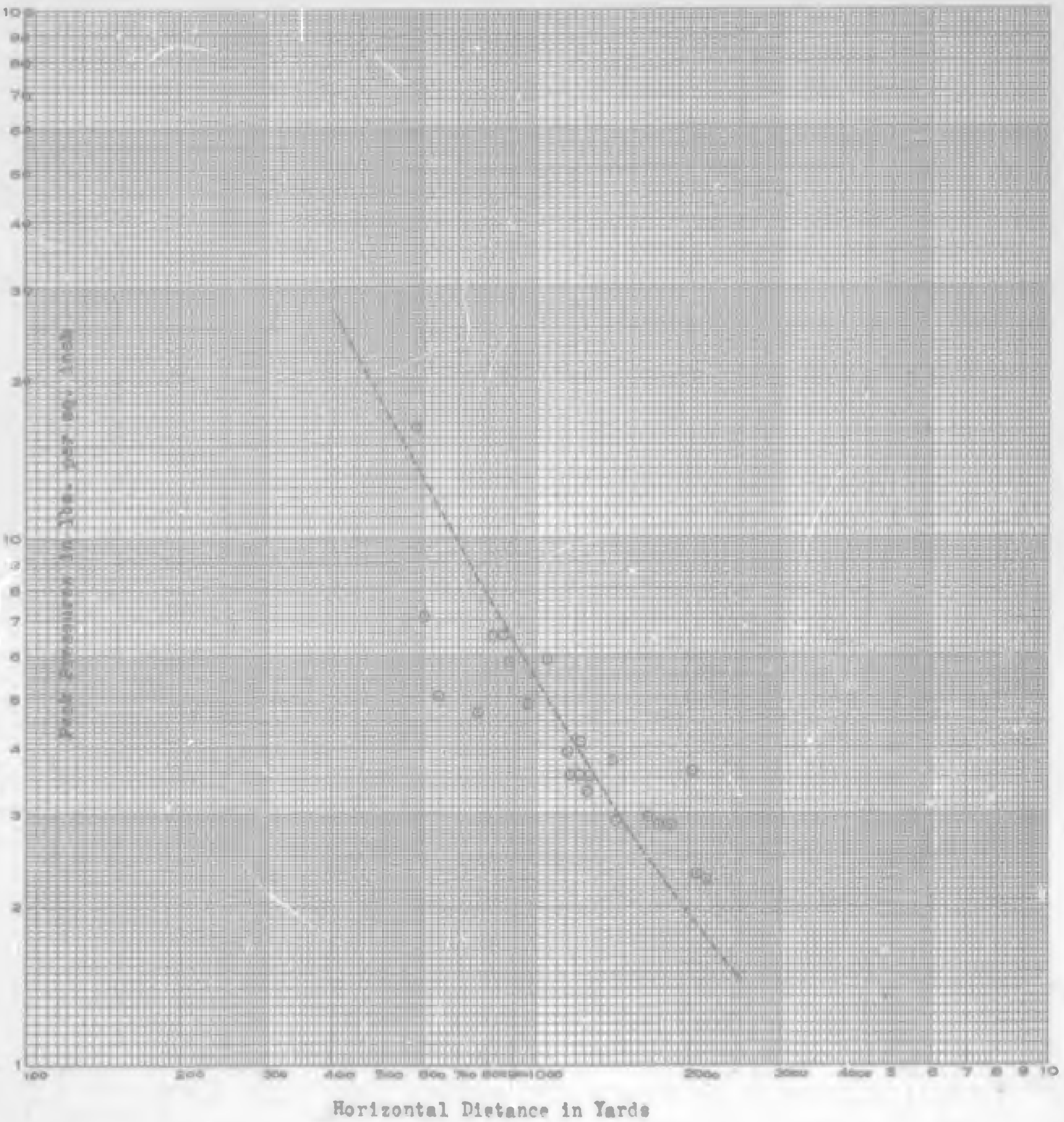


Figure 5

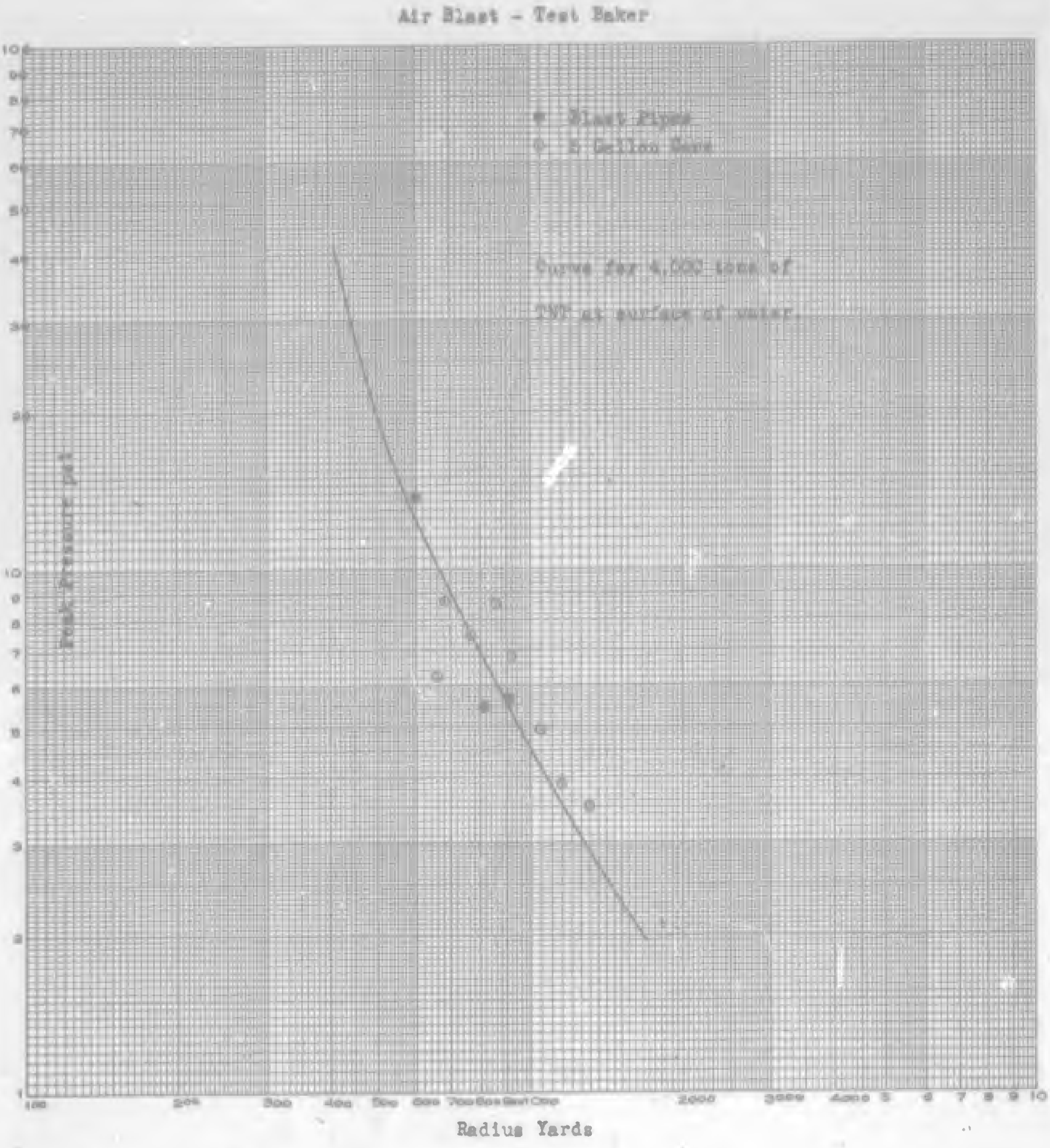

Air Blast - Test Baker
● Blast Pipes
○ 5 Gallon Cans
Curve for 4,000 tons of
TNT at surface of water.
Peak Pressure psi
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
100
200
300
400
500
600
700
800
900
1000
2000
3000
4000
5
6
7
8
9
10
Radius Yards

Figure 6

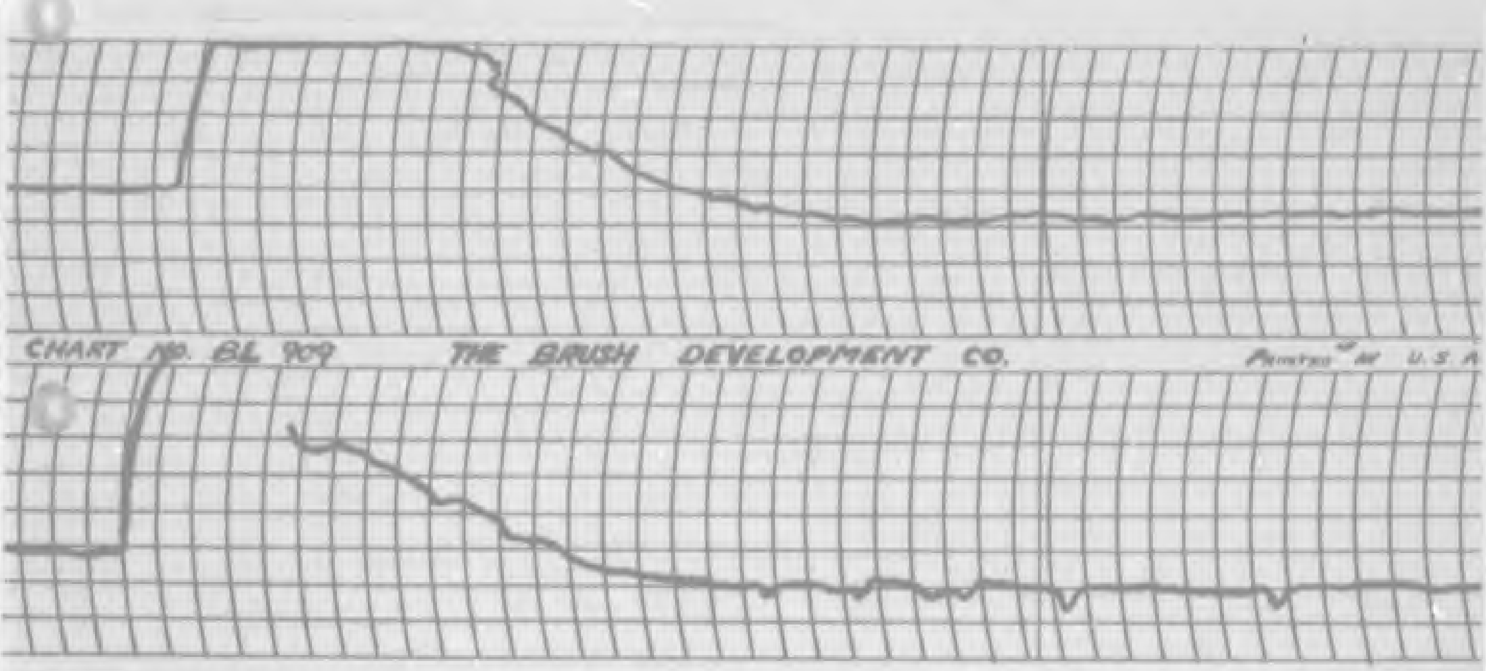


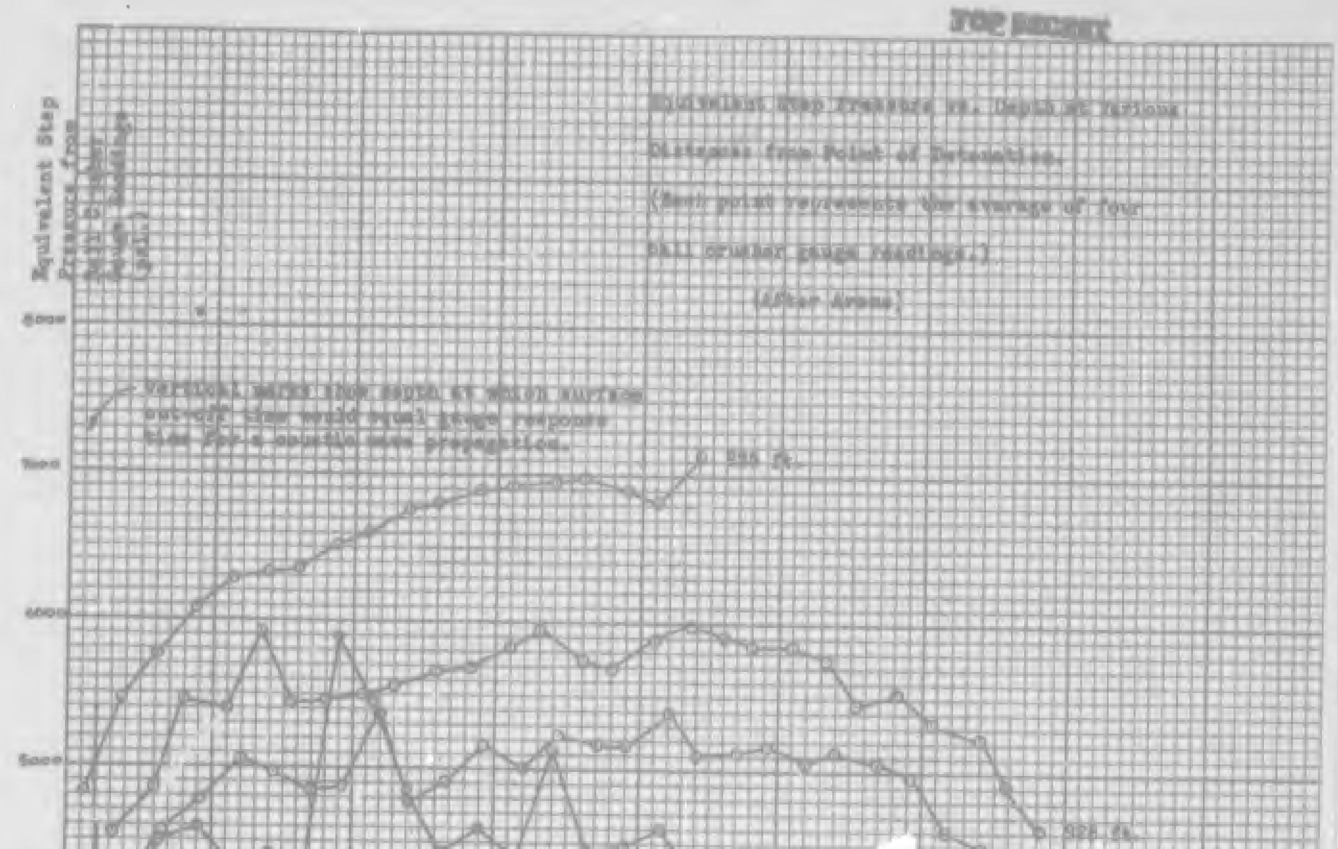
Figure 7 (from Tamarkin)

APA 65 Briscoe 900 yds.
AirBlast records on Shot Baker

Top Trace
Starboard hull
Pressure sensitivity 0.11 psi/mm
Time Scale 0.00764 secs/mm
Peak Pressure = 5.8 psi; Positive duration = 0.56 secs.

NOTE: This record was partially off-scale and the peak pressure given is estimated on the basis of extrapolatation of that part of the record which is on scale.

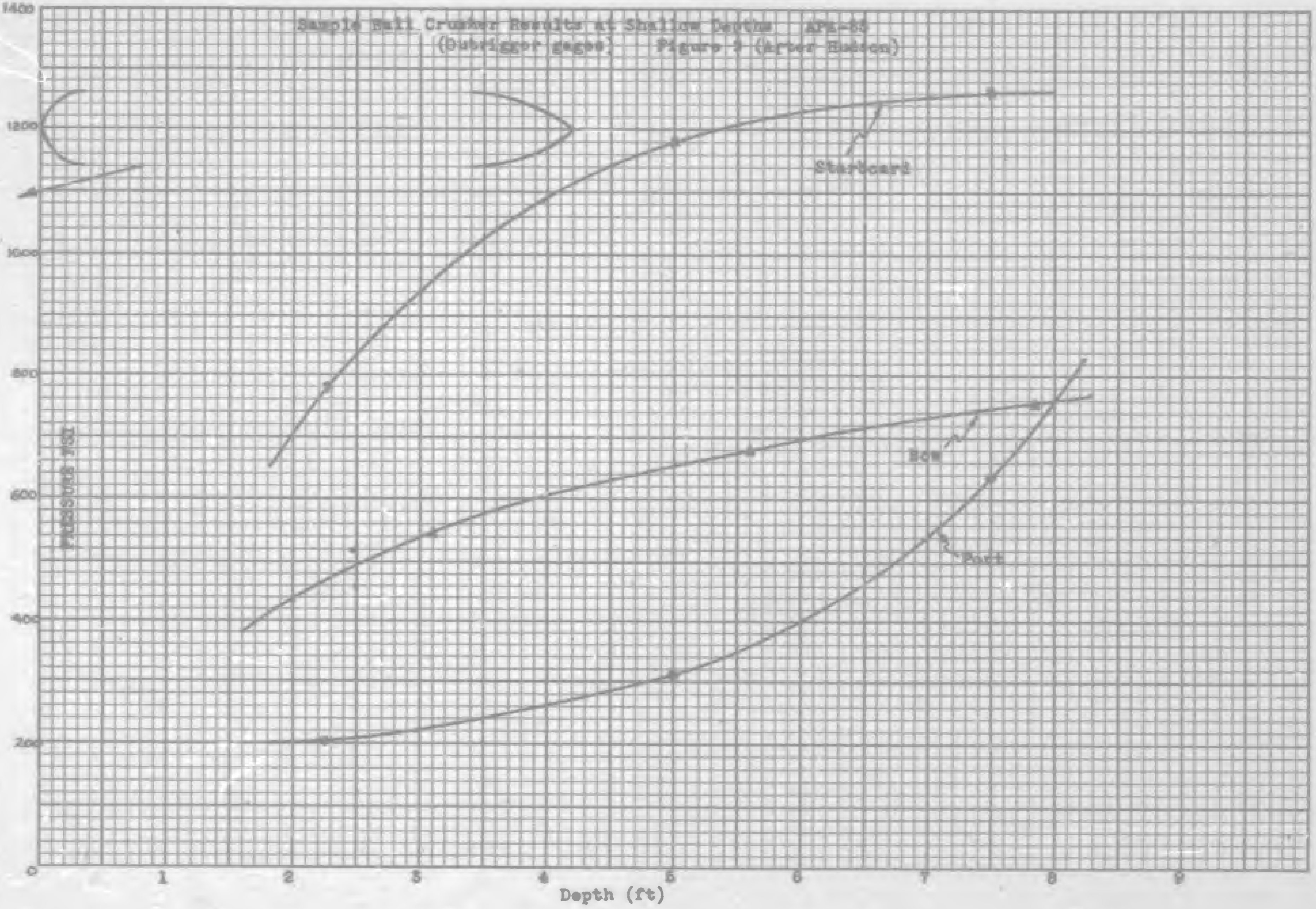
Bottom Trace
Port hull
Pressure sensitivity 0.21 psi/mm
Time scale 0.00764 secs/mm
Peak Pressure = 6.5 psi; Positive duration = 0.48 secs.



Equivalent Step Pressure vs. Depth at Various Distances from Point of Detonation.
(Each point represents the average of four ball crusher gauge readings.)
(After Arons)

Figure 8

TOP SECRET



Sample Ball Crusher Results at Shallow Depths APS-65
(Outrigger gages) Figure 9 (After Hudson)

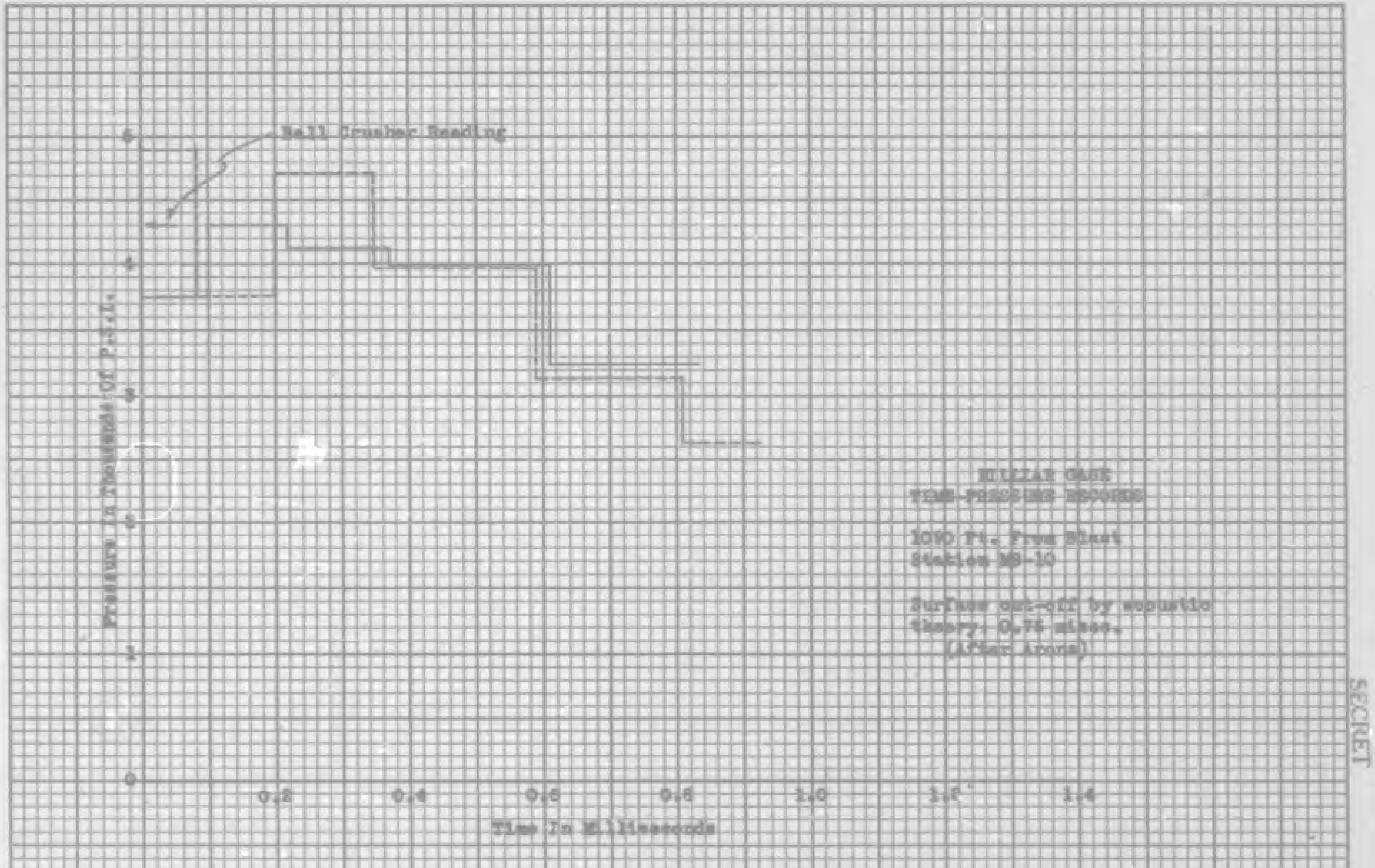

Ball Crusher Reading
HILLIAR GAGE
TIME-PRESSURE RECORDS
1090 Ft. From Blast
Station MB-10
Surface cut-off by acoustic
theory: 0.76 msec.
(After Arons)
Pressure In Thousands Of P.S.I.
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time In Milliseconds

Figure 10

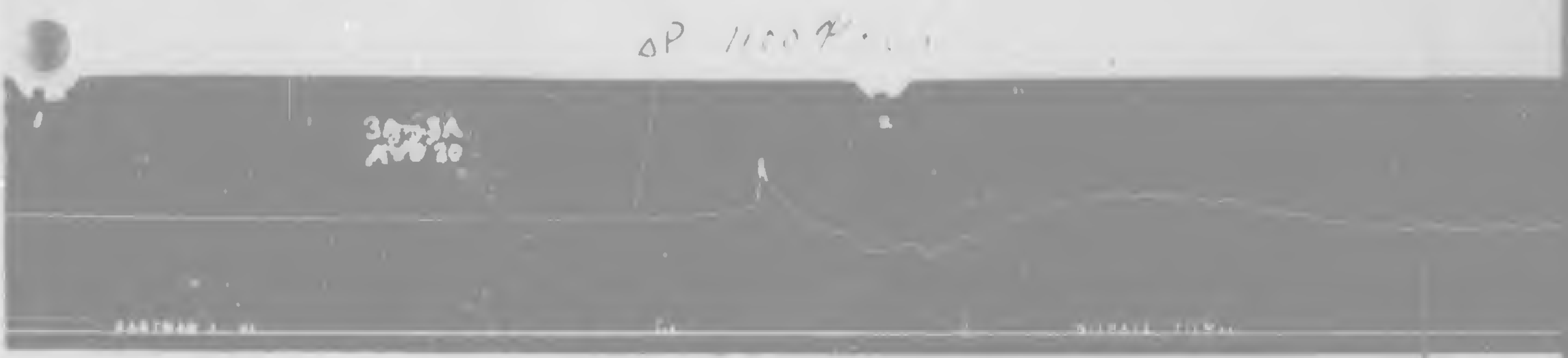


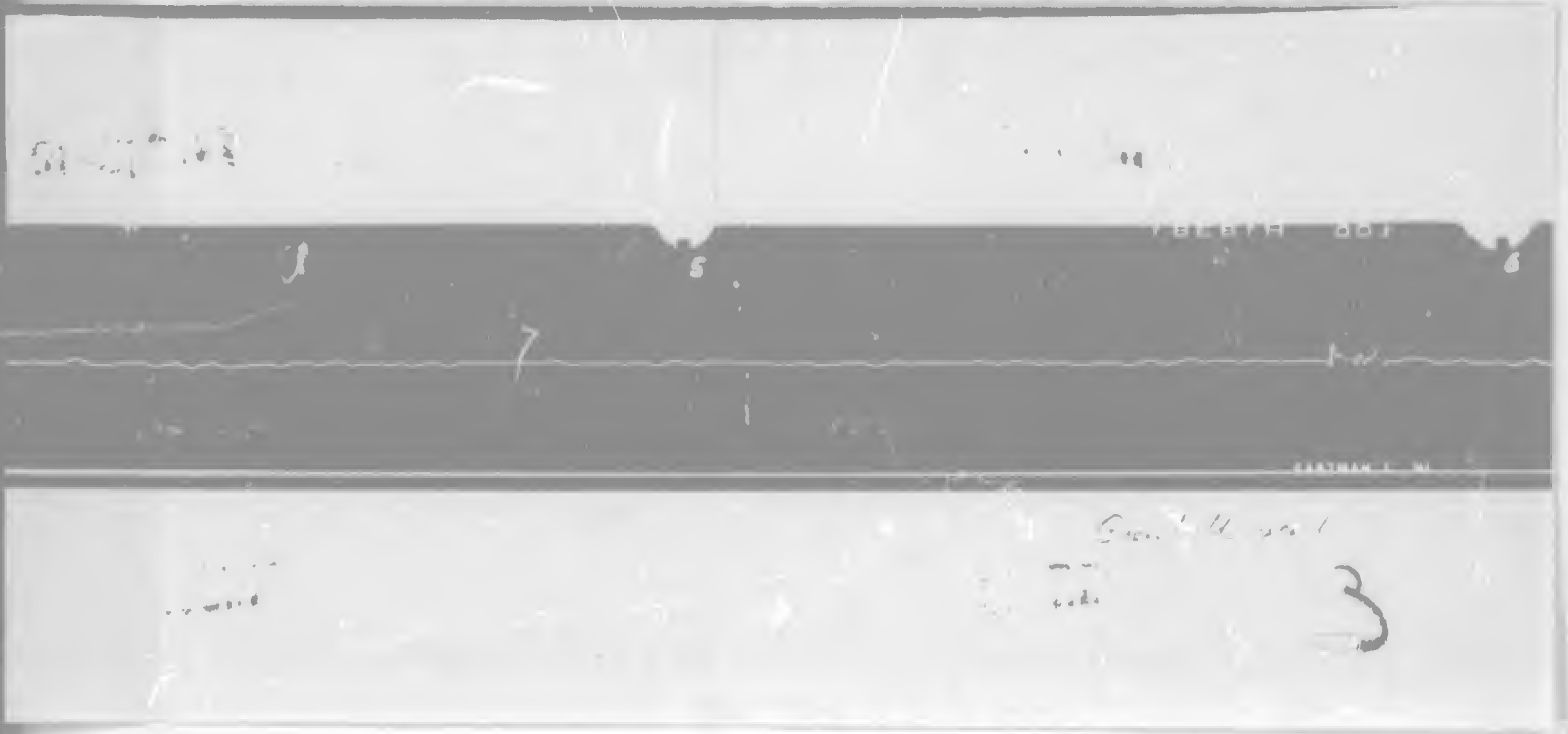
FIGURE 11.

A piezo electric gauge recording on a magnetic wire.

Peak pressure in the first pulse is 1100 ± 60 psi

(after Greenfield)

2


5
6
3

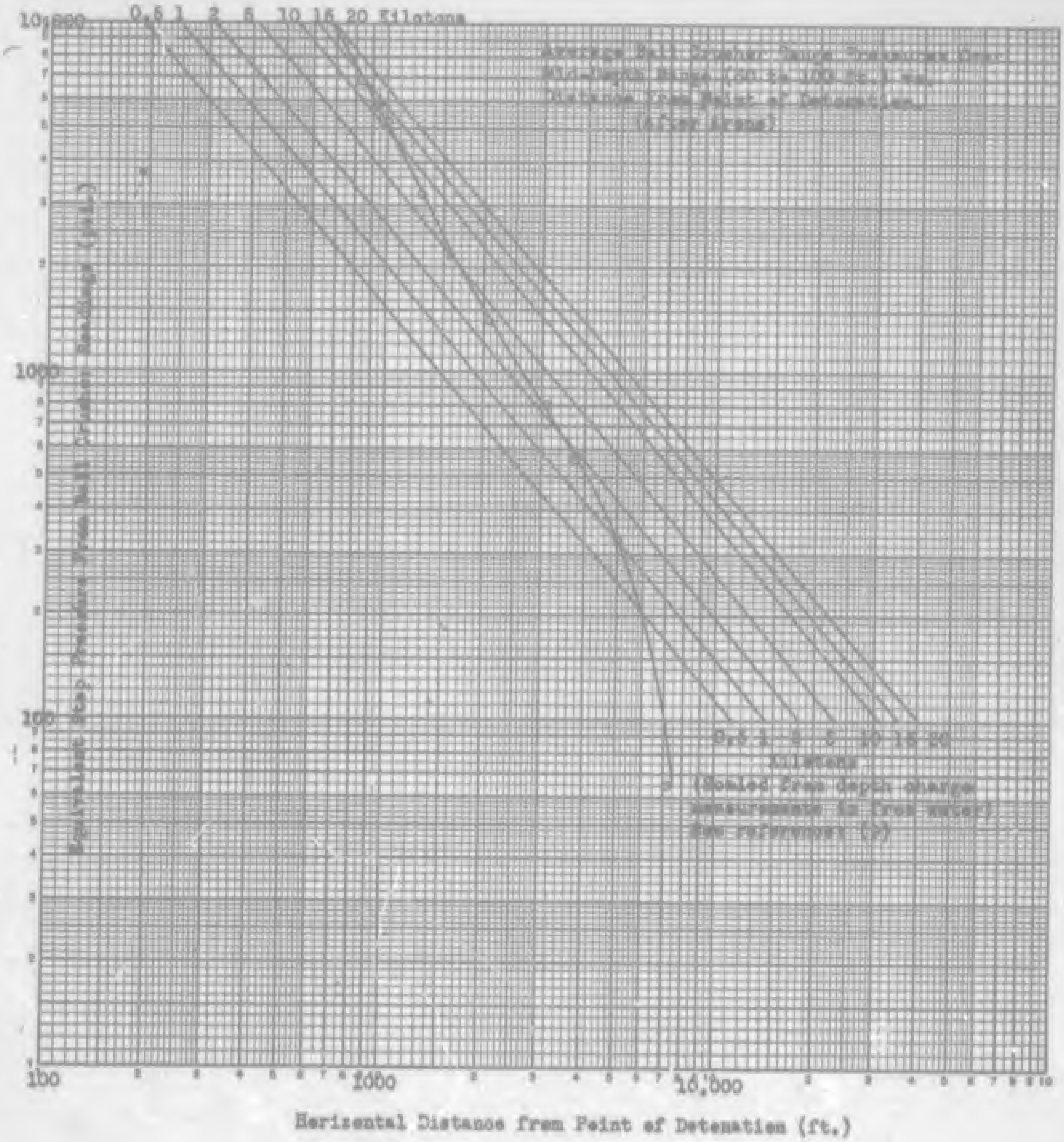

0.5 1 2 5 10 15 20 Kilotons
Average Ball Crusher Gauge Pressures Over Mid-Depth Range (20 to 100 ft.) vs. Distance from Point of Detonation.
(After Arons)
0.5 1 2 5 10 15 20
Kilotons
(Scaled from depth charge measurements in free water)
See reference: (5)
Equivalent Peak Pressure From Ball Crusher Readings (psi.)
10,000
1000
100
100
1000
10,000
Horizontal Distance from Point of Detonation (ft.)

Figure 12

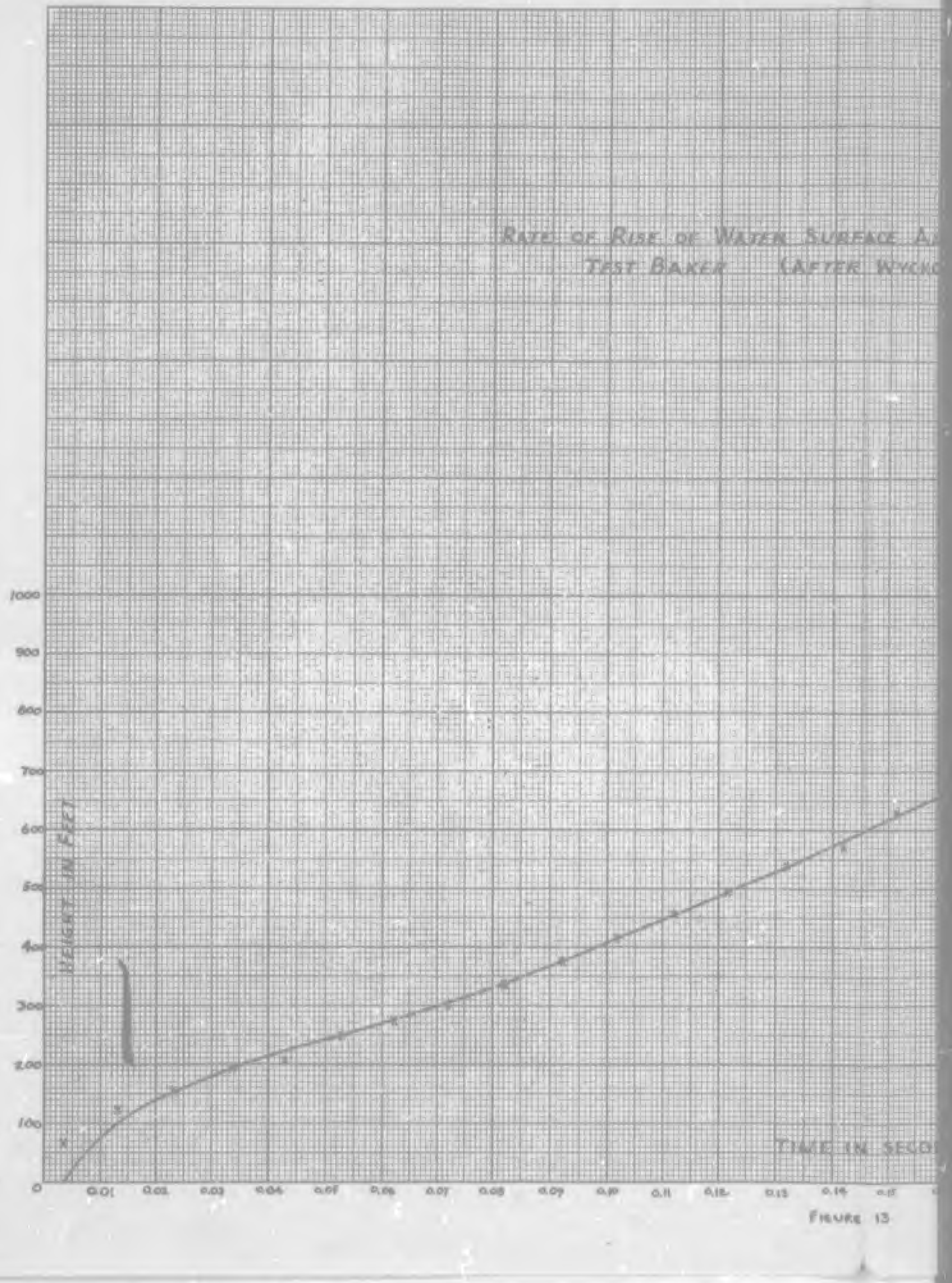

RATE OF RISE OF WATER SURFACE A
TEST BAKER (AFTER WYCK
HEIGHT IN FEET
1000
900
800
700
600
500
400
300
200
100
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
TIME IN SECO

FIGURE 13

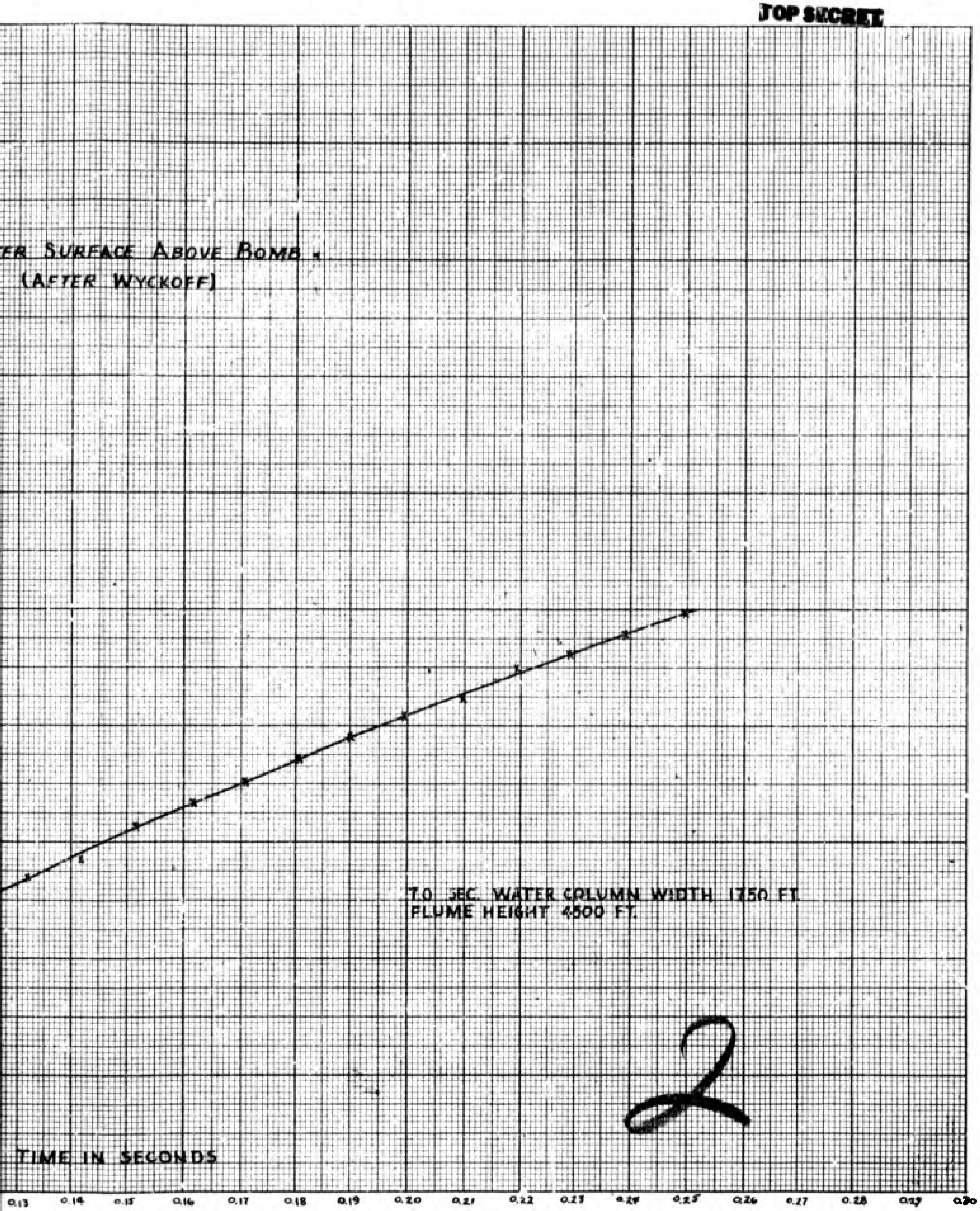
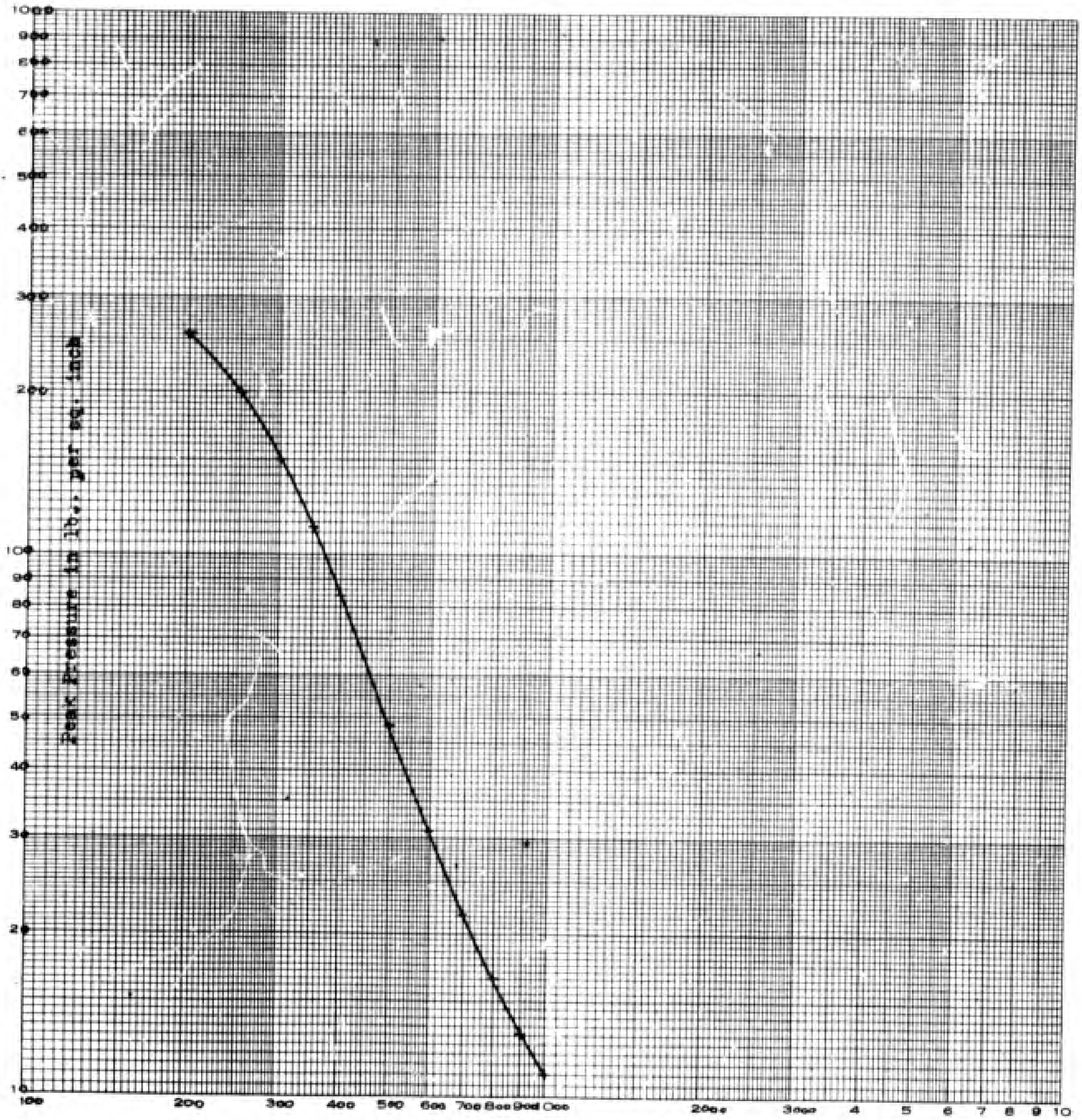

ER SURFACE ABOVE BOMB *
(AFTER WYCKOFF)
7.0 SEC. WATER COLUMN WIDTH 1750 FT.
PLUME HEIGHT 4500 FT.
TIME IN SECONDS
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
0.21
0.22
0.23
0.24
0.25
0.26
0.27
0.28
0.29
0.30

FIGURE 13

2

Air Blast Pressure Distance curve derived from

Photographic measurements of shock wave velocity (Test Able)



Horizontal Distance in Yards

Figure 14

Air Blast Pressure Distance Curve (Test Able)

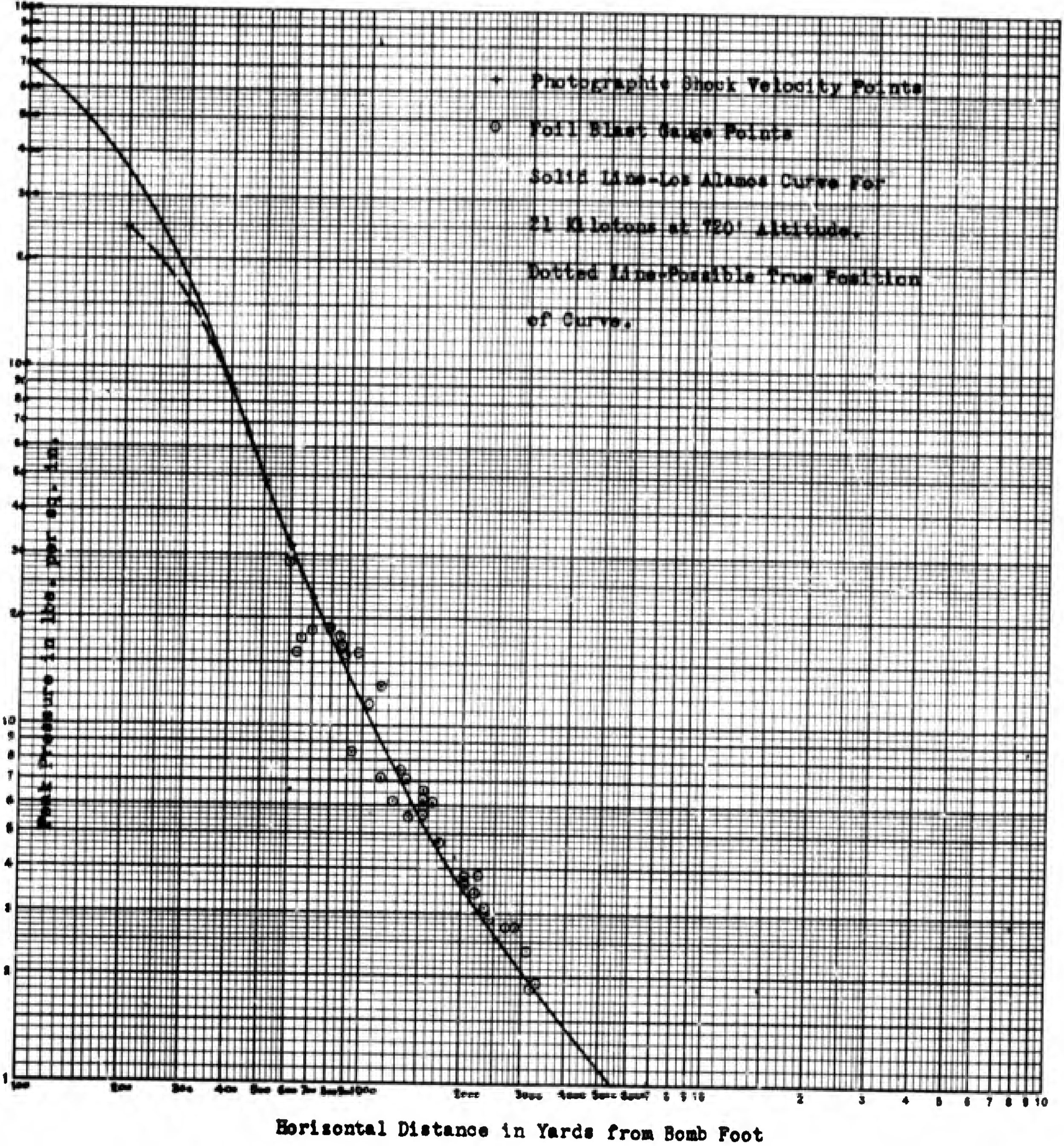


Figure 15

SECRET

ENCLOSURE D

"Origin of the Second and Higher Pulses",

"Reasons for Expecting the Peak Pressure in Baker to Fall Off with Radius Faster than R^{-1}",

and

"The Structure of the Water Spout"

by

Dr. W.G. Penney

TABLE OF CONTENTS

INTRODUCTION

The following two reports entitled (1) "Origin of Second and Higher Pulses. Acoustical Theory" and (2) "Reasons for Expecting the Peak Pressure in Baker to fall off with Radius faster than R", give a gross interpretation of the underwater results observed in Test B.

The outstanding experimental results were (1), that the pressure, had a duration much greater than expected and (2), that a second pulse of great damaging power was observed about 100 milliseconds after the first.

The reason the pulse lasted longer is because a shock wave of pressure P cannot propagate at an angle of incidence less than a certain critical angle Θ depending on the value of P. The pressure pulse near the surface in Test B was therefore inclined at a slightly greater angle than would be expected from geometrical optics. The pulse behaved as if it came from greater depth, and calculation of the details of the hydro-dynamics shows that the durations expected by this theory agree well with those observed.

The interpretation of the second shock is undoubtedly to be sought in reflections or multiple reflections from the bottom. Whether the proposal made in the enclosed reports will prove to be substantially correct is not yet clear, but there is no doubt that the true explanation lies in the directions indicated.

The suggestion is made that the ship damage results found in Test B would be very similar to those produced by another arrangement of the bomb and the particular ship concerned. The depth at which the bomb is to be placed to produce the same damage on the ship can be calculated if the peak pressure of the underwater blast in Test B is known at a depth equal to the draught of the ship.

Finally, some remarks and suggestions are made about the structure of the water spout. Strong reasons are given for supposing that all of the water in the spout came from the central regions of the explosion. The water in the spout did not spring vertically upwards from the water surface of the lagoon. The total amount of water in the spout and water clouds at the top of the spout probably did not exceed 50,000 tons in contrast to earlier estimates of one to ten million tons.

ORIGIN OF THE SECOND AND HIGHER PULSES ACOUSTICAL THEORY

The following remarks are based on an idea which will probably need considerable extension. They are put forward in the hope of stimulating further experimental work, because it is considered that an accurate theory must very largely await guidance from experiment.

The outstanding result of the underwater pressure-time curves from Test B is the appearance of a second pulse following the first pulse at a time interval ranging from 10-50 milliseconds after the primary pulse. Some of the records indeed show a third pulse, but this is very much weaker than the first two, which are usually of roughly equal peak pressure and impulse. The experimental evidence so far available indicate that the time interval between the first and second pulses decreases with radius, roughly as the inverse of the radius. The duration of the pulses themselves are both 2-5 milliseconds, and the pulses are approximately step-functions.

It is proposed to apply the theory of sound, assuming that the surface of the water is a perfect free surface, and that the bottom is a reflector or reflection coefficient j. Since it is impossible to solve the non-linear equations for the motion near the center, it is proposed to assume that the initial wave of pressure is a spherical band extending from top to bottom. The pressure in the band is taken to be a step-function of thickness 0.003c, where c is the velocity of sound. The thickness is therefore about 15 ft. Now we apply the theory of sound, using the method of images. The image of any source (either the primary source, or itself an image) changes sign at reflection in the free surface and retains its magnitude; the image of any source in the bottom retains its sign but decreases in magnitude by j.

The image system which solves the problem is shown diagrammatically.

All images are point sources located at the mid-point of their section, on a vertical line through the primary source. The images are shown displaced in the diagram, in order to show which image is the image of any other image.

Suppose that the depth of water is 0.036c (i.e. 180 ft). Let us now obtain the pressure-time curves at mid-depth and at the bottom at a radius 0.36c (i.e. 1800 ft). For simplicity, let us neglect the fact that the magnitudes of the step functions in the pressure pulse are not all equal at the field point, because some of the images are further away than others. Thus, as far as peak pressures are concerned, we assume that all are equal.

It will be found that the pressure-time curve at the field point consists of a number of steps, separated in time, and that the only overlapping of steps occurs in the initial pulse. Table I and Table II give the numerical values.

TABLE I.

Pressure-time relations at 1800 ft, mid-depth

Time Milliseconds	Pressure step Arbitrary units	Pressure step j = 0.707	Energy in step Arbitrary units
0 - 1.8	1.0	1.0	1.80
1.8 - 3.0	j	0.71	0.60
3 - 4.8	$-(1 - j)$	-0.29	0.15
7.2 - 10.2	0	0	0
10.2 - 13.2	$-2j$	-1.41	6.0
13.2 - 16.2	0	0	0
16.2 - 19.2	$j(1 - j)$	0.21	0.13
19.2 - 28.2	0	0	0
28.2 - 31.8	$2j$	1.0	3.0
31.8 - 45	0	0	0
45 - 48	$-j^2(1 - j)$	-0.15	0.07
48 - 57.8	0	0	0
57.8 - 60.8	$-2j^3$	-0.71	1.50

TABLE II.

Pressure-time relations at 1800 ft, bottom

Time Milliseconds	Pressure step Arbitrary units	Pressure step j = 0.707	Energy in step Arbitrary units
0 - 3	$1 + j$	1.71	8.7
3 - 3.6	0	0	0
3.6 - 6.6	$-1-j$	-1.71	8.7
6.6 - 10.8	0	0	0
10.8 - 13.8	$-j-j^2$	-1.21	4.36
13.8 - 21.6	0	0	0
21.6 - 24.6	$j + j^2$	1.21	4.36
24.6 - 36	0	0	0
36 - 39	$+j^2 + j^3$	0.85	0.22
39 - 54	0	0	0
54 - 57	$-j^2 - j^3$	-9.85	0.22

Figures I and II show the pressure-time curves. It will be noticed that there is an appreciable difference between them. The negative pulses are not likely to be observed as negative; the water probably cavitates.

The striking feature of the curves is the appearance of a strong second pulse. Of course, the value $j = 0.707$, chosen for the reflection coefficient, was made in order to ensure that the second pulse was large. This value is higher than might have been anticipated, but it must be remembered that the reflections are of comparatively weak and very long pulses, and the value chosen for j does not seem to be entirely unreasonable.

If the tentative suggestion made above for the origin of the second pulse is correct, it follows that the time interval between the first and second pulse at mid-depth should obey

$$T = 29 \frac{(1800)}{(R)} \text{ milliseconds}$$

while at the bottom it should obey

$$T = 22 \frac{(1800)}{(R)} \text{ milliseconds}$$

It will be seen from the tables that the pulses following the primary pulse contain a large part of the energy.

The ideas put forward above suggest that the duration of the first step of the primary pulse at the surface is zero and increases with depth. The maximum pressure in the first pulse can be 1.7 times the initial shock pressure, and if this occurs, it will occur at mid-depth or below. To describe all the phenomena and all the cases that can arise would take a lot of space, but the reader should have no difficulty in constructing the theoretical values for any situation in which he is interested. Enough, however, has been said to demonstrate that the pressure-radius-time surface is extremely irregular, with many abrupt discontinuities. When additional experimental complications, such as irregularities on the bottom, are introduced, and when the additional fact is remembered that a proper theory incorporates all of the above ideas as well as many other much more complex features, it is clear that the Test B results, and further model studies, must be studied for a long time before the general picture emerges.

Finally, there is one important test which could be made. The peculiar effects which have been obtained above depend on the presence of the bottom. If a shallow explosion were made in deep water, the second pulse should be absent, and we should be reduced to ordinary acoustical theory with a single free surface. While it is certain that acoustical theory is not entirely adequate to describe the phenomena for a shallow explosion in deep water, it still has not been proved experimentally that there is a bad failure. If such an experiment showed a second pulse, we should conclude that it arose either from the non-linear nature of the motion, or from a rapid pulsation of the cavity. Then we should at least know that the second pulse in Test B did not arise from a second explosion (possibly a hydrogen-oxygen detonation; considered to be extremely unlikely).

Further consideration may show that the ideas now put forward are not valid. For example, it has been assumed that negative pulses can be propagated and reflected off the bottom. While this is no doubt true provided the actual pressure never becomes negative (or, let us say, less than the tinsile strength of water, 200 psi), due to the simultaneous presence of a pressure pulse, its accuracy may be doubted if it is necessary to assume that the pressure actually is negative. However, the Bikini second pulse is a clearly observed phenomena, and earlier model experiments made at the Taylor Model Basin apparently also give the same effect. Alternative explanation is undoubtedly a property of an explosion in a sheet of water with an isotropic, partially reflecting bottom.

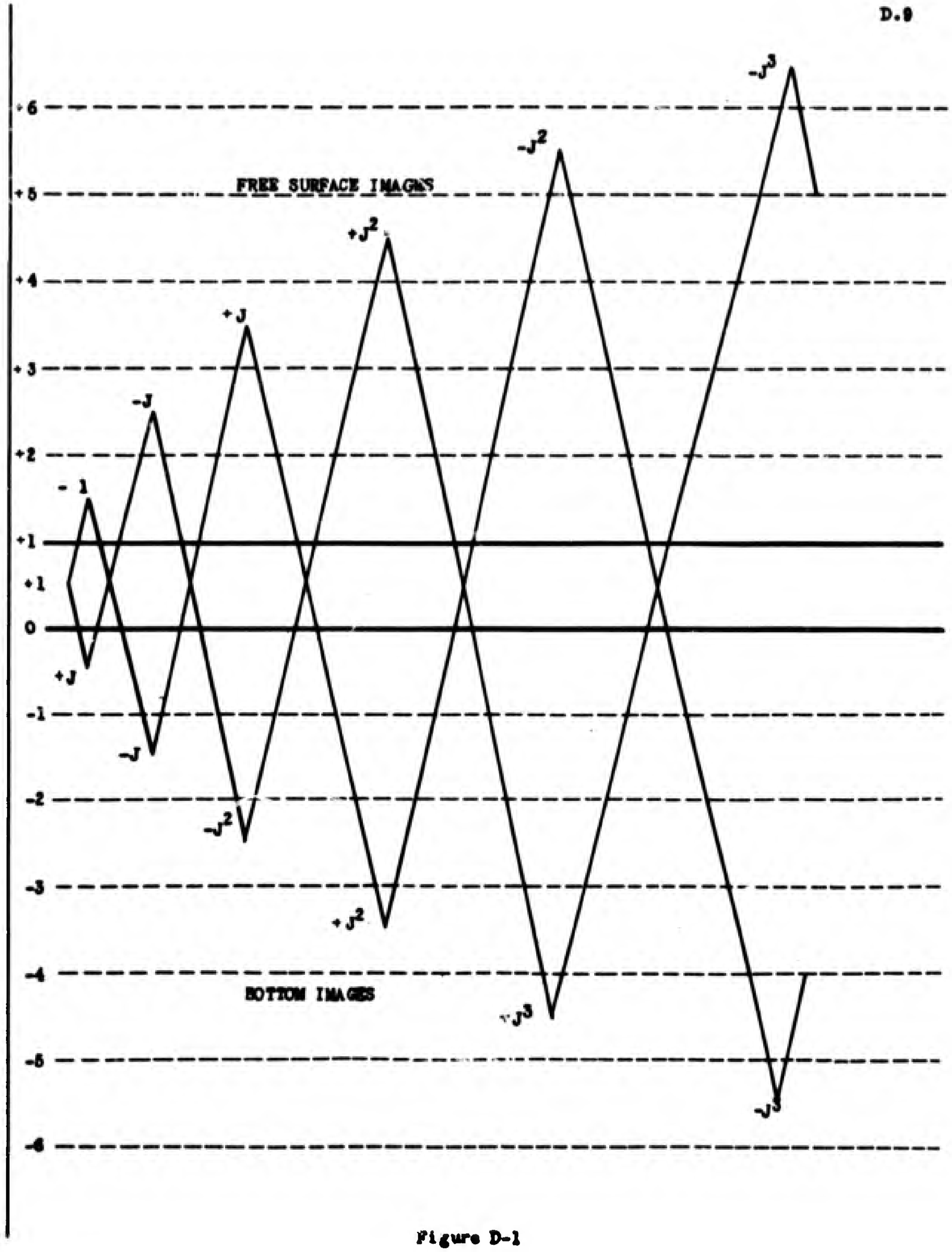
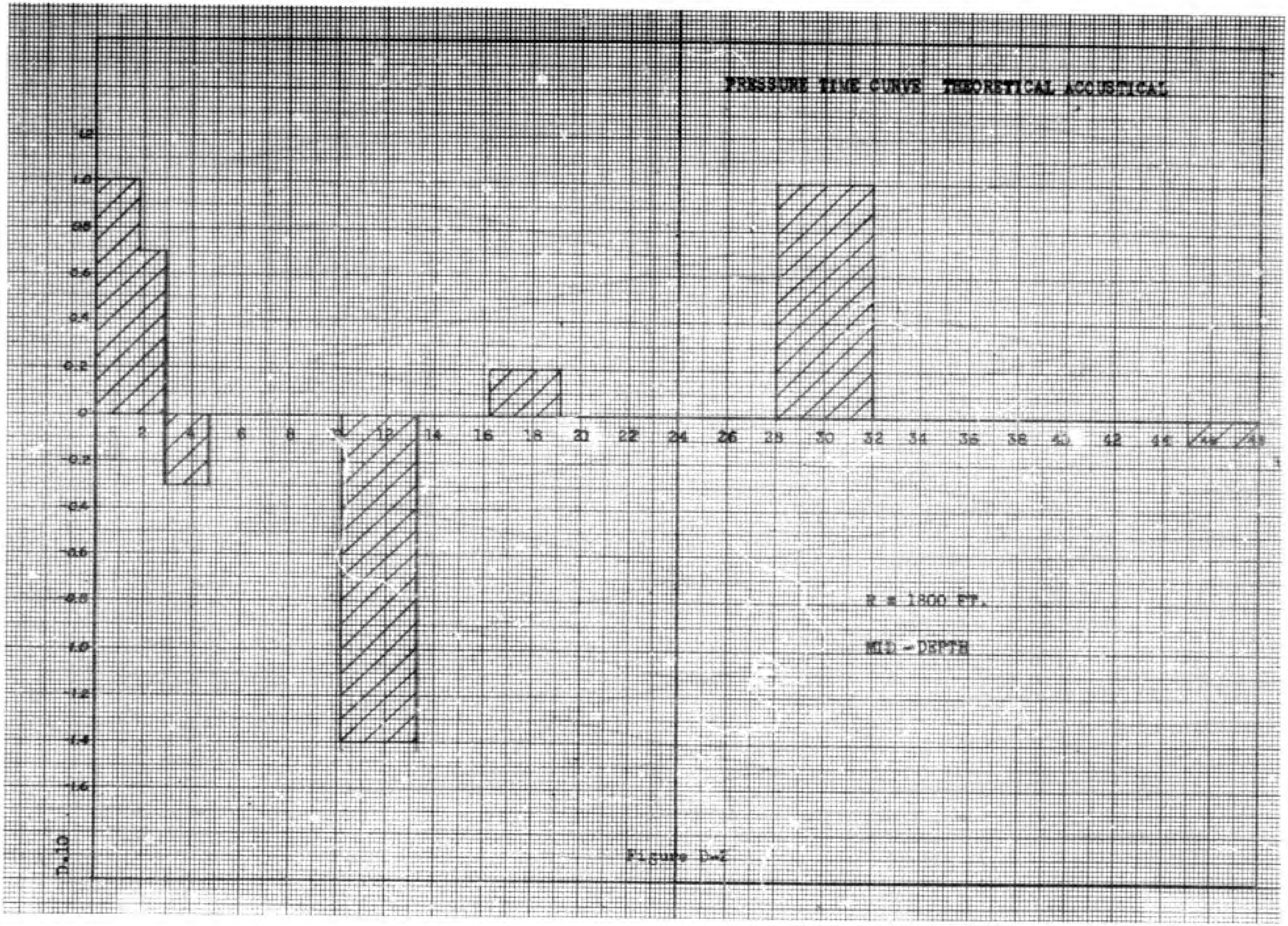

-J3
+6
-J2
FREE SURFACE IMAGES
+5
+J2
+4
+J
+3
-J
+2
- 1
+1
+1
0
+J
-1
-J
-2
-J2
-3
+J2
-4
BOTTOM IMAGES
+J3
-5
-J3
-6

Figure D-1

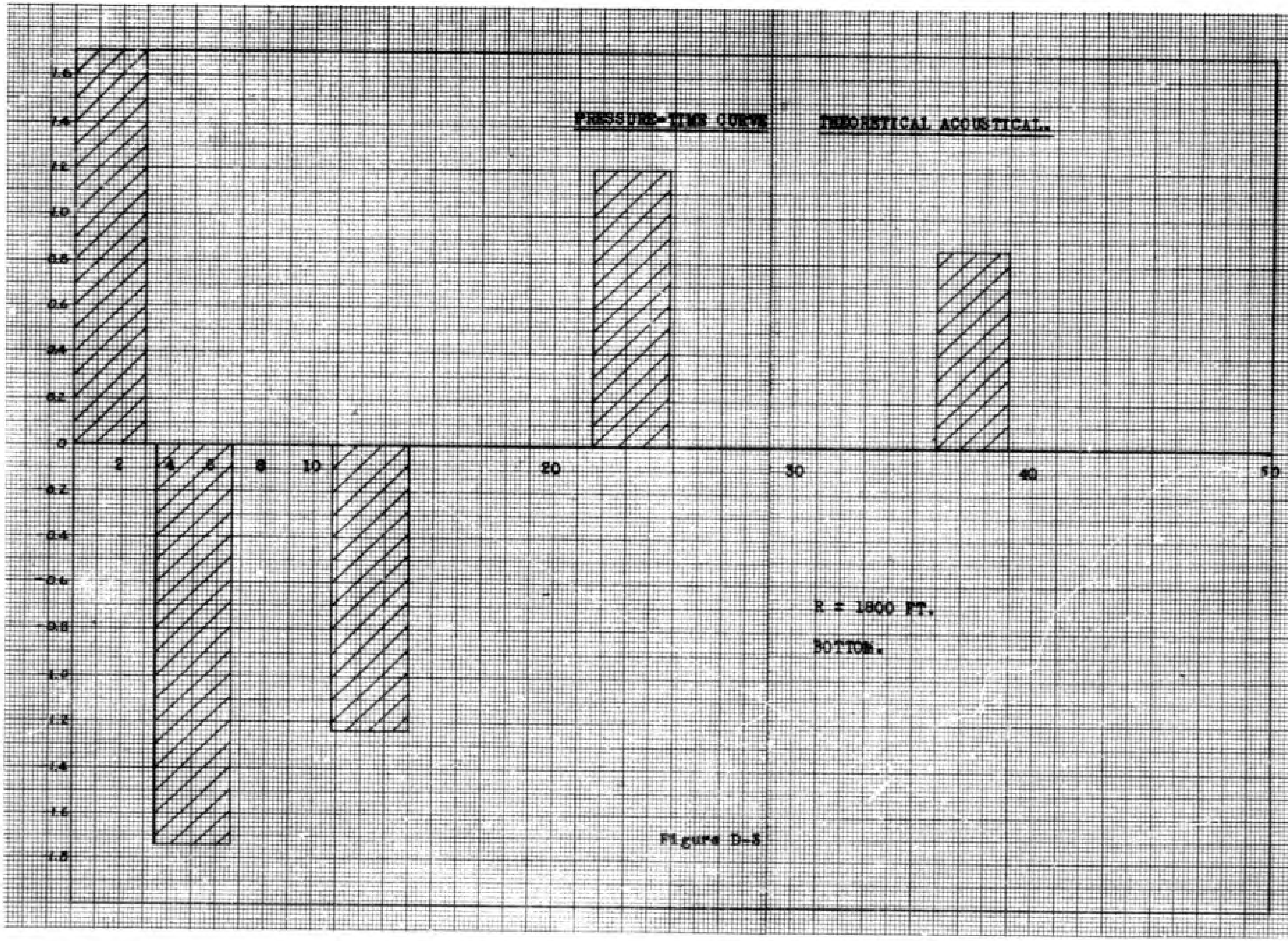


PRESSURE TIME CURVE THEORETICAL ACCOUSTICAL

R = 1800 FT.

MID - DEPTH

Figure D-2



PRESSURE-TIME CURVE THEORETICAL ACOUSTICAL.

Figure D-5

REASONS FOR EXPECTING THE PEAK PRESSURE IN BAKER TO FALL OFF WITH RADIUS FASTER THAN R^{-1}

The pressure pulse generated by an explosion in deep water obeys the laws of the spherical propagation of sound reasonably well. However, as is well known, the peak pressure falls off a little faster than the inverse radius (more like $R^{-1.27}$ than the theory of sound law R^{-1}), while the positive duration increases slightly, with increasing radius (instead of remaining constant, as it does in the theory of sound). Elementary arguments based on non-linear propagation indicate that the rate of decay of pressure with radius in Test B should be much faster than the rate of decay in deep water propagation. The arguments amount to a demonstration of the failure of the Meyer corner solution for a plane shock in water.

Let us consider the conditions which are necessary for the oblique incidence of a plane water shock on a free surface. We are interested in the case where the shock pressure exists all the way to the surface, even though the pressure at the surface may have a duration tending to zero as the surface is approached. A solution may be had from the well-known Meyer corner solution. For convenience, let us suppose that the shock front is reduced to rest by the artifice of superimposing a horizontal velocity on the whole of the water. The situation is shown in the diagram. (Figure 4)

Following the stream lines from right to left, the particle velocity in the zero free pressure region is U sec θ, where U is the shock pressure in still water corresponding with pressure p. At the shock front OS, the particles receive an extra component u perpendicular to the shock front. The compounded velocity v is shown in the triangle of forces clearly

$$v^2 = (U \operatorname{Sec} \theta - u \operatorname{Cos} \theta)^2 + (u \operatorname{Sin} \theta)^2$$

$$= U^2 \operatorname{Sec}^2 \theta + u^2 - 2 U u \qquad (1)$$

Normally, the flow at speed v and pressure p is supersonic. An angular rarefaction wave begins along a radius from O, usually at the Mach angle beyond OM. However, in the critical case in which we are interested, the angular rarefaction wave begins as early as possible, along the perpendicular OM. The stream lines all emerge eventually parallel to OF, and again return to zero pressure. In this solution it will be seen that the duration of the peak shock pressure p near the surface is proportional to depth, and vanishes at zero depth (just like the accoustical theory). If, however, v is less than the velocity of sound at pressure p, the whole solution collapses, and the rarefaction penetrates into the high pressure triangle MOS. This means that if an initial system like that shown in the diagram is artificially established at t = o, with the aid of rigid smooth walls, and the walls are then removed, a rarefaction will start from O and spread downwards into the water. The critical condition is

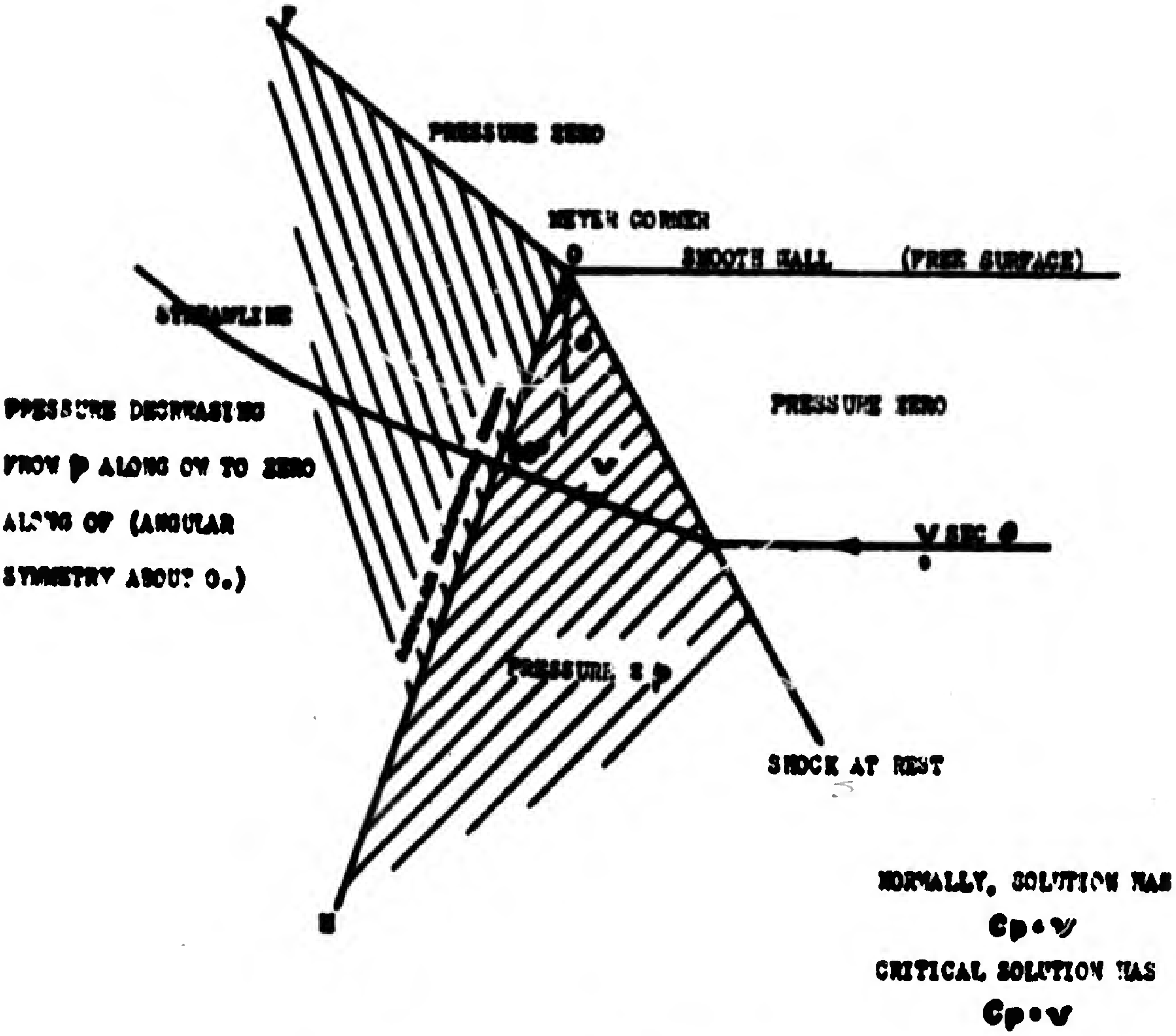
$$v = Cp$$

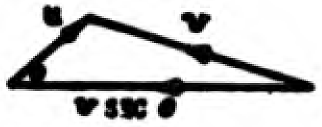
or

$$\operatorname{Sec}^2 \theta = (Cp^2 + 2 U u - u^2)/U^2 \qquad (2)$$

This formula gives us the smallest angle θ at which a given shock of pressure p can maintain itself at a free surface.

CRITICAL CASE OF MEYER SOLUTION.





TRIANGLE OF VELOCITIES

Figure 4.

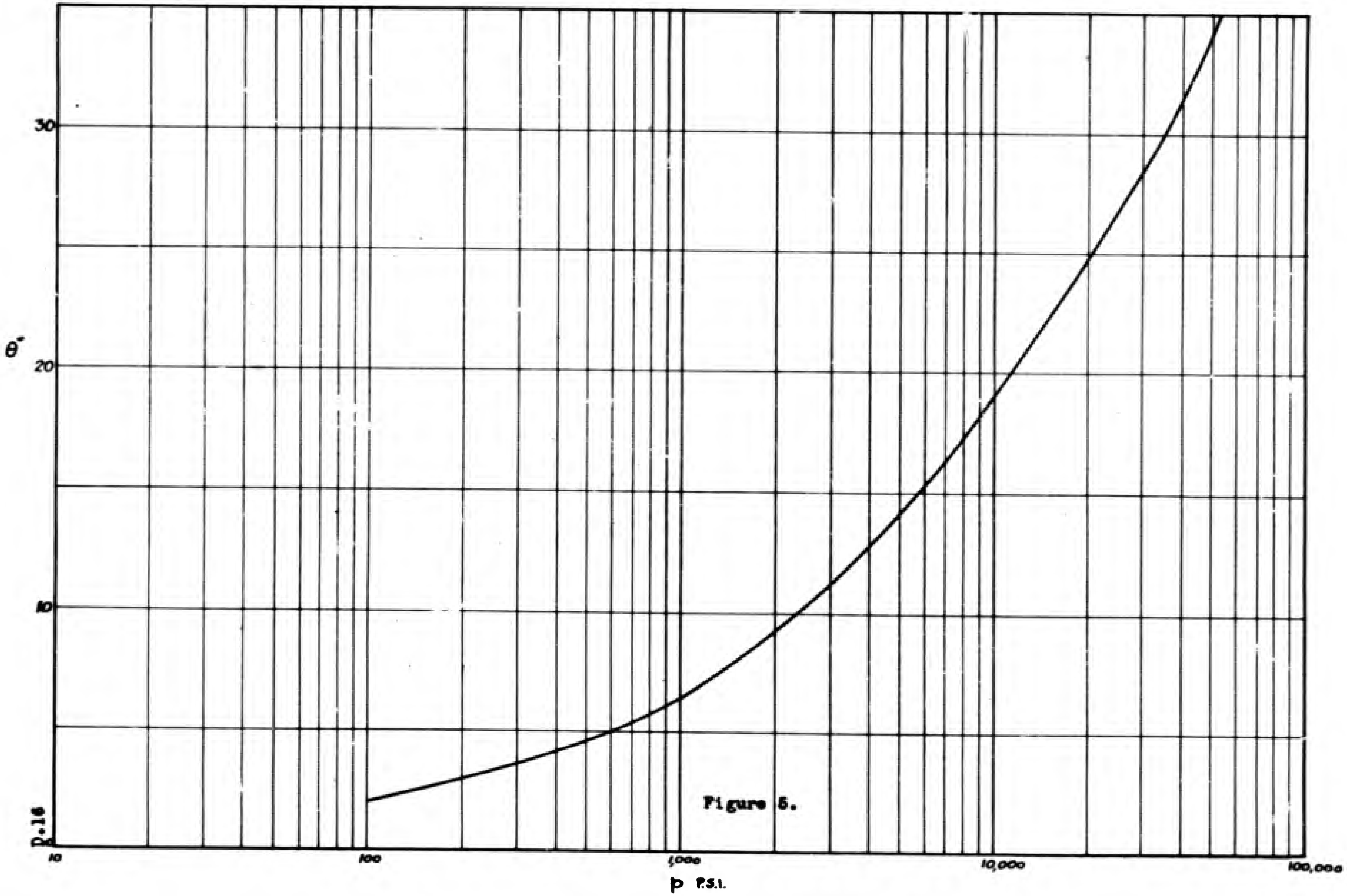


Figure 5.

Now, the ordinary shock equations give

$$U\,u = v_0 p, \qquad u^2 = p\,(v_0 - v_1)$$

where v_0 is the volume of one gramme of water at atmospheric pressure.

Using the equation of state

$$v = \frac{1.166}{(3 + p)^{0.138}}$$

where p is in 10^3 kilograms/cm^2 (14220 psi), we find

$$\cos^2\theta = \frac{p}{1 - \left(\frac{3}{3+p}\right)^{0.138}} \; \frac{1}{\frac{1}{0.138}\,3^{0.138}\,(3 + p)^{0.862} + p\left\{1 + \left(\frac{3}{(3+p)}\right)^{0.138}\right\}}$$

If p is small compared with 3, then

$$\theta = 25\,p^{\frac{1}{2}} \text{ degrees}$$

Expressing p in psi, $\theta = 0.21\,p^{\frac{1}{2}}$ degrees (3)

Values of θ computed for various values of p are given in the table

p psi	100	400	1000	4000	10,000	30,000	70,000
θ°	2.1	4.3	6.5	12.7	19.0	28.4	38.5

These results are shown in Figure 5.

The stream lines for a shock advancing into still water could be computed by solving the Meyer equations, and then superimposing the velocity U sec θ on the system. This is a matter of calculation and nothing unusual can arise.

Let us now see what are the consequences of applying the above theory to a shallow explosion in water. As the shock wave strikes the surface, the angle of incidence of the wave is 90°, and this is of course larger than the critical angle for a shock wave of any intensity. As the shock spreads along the surface, the angle of incidence decreases, but the peak pressure decreases and with it the corresponding critical angle. The question is whether the critical angle θ for the peak shock pressure (this peak corresponding with the free water pressure) decreases to a value less than the angle of incidence. If this does not happen, the acoustical theory is a reasonable approximation. The pressure near the surface does not reach the free water pressure, although the positive duration tends to zero as the surface is approached. By examination of the numerical quantities involved, it is found that the minimum depth of explosion that will succeed in propagating the free water pressure p psi for an explosion of 20,000 tons of TNT depends on p in the manner shown in Figure 6. The least pressure that must cause much damage is probably between 1000 and 2000 psi. Hence the minimum depth is roughly 400-500 ft. For purposes of comparison, the results for a 360 lb charge of TNT are also shown.

In the case of a really shallow explosion, the critical condition is very quickly passed. Refer to Figure 7. Suppose that SF is the wave front at the moment the front reaches the critical angle θ for the pressure at the front, from the point S outwards, a rarefaction zone in which the pressure is less than the free water pressure must spread from the surface downwards. At any stage, the pulse below a certain depth will be unaffected, and this depth will increase with radius. Let S'B denote the surface below which the front of the pulse has not been affected, and suppose that AB is that part of the pulse in the smaller pressure region. The pressure at A may be estimated by the following argument which is not exact but must be fairly close to the truth.

The horizontal radius through the centre of the explosion OH is increasing at the rate U_f where U_f is the shock velocity at the free-water pressure at H. The point A must be keeping in step with H, and we therefore take as the velocity of A the quantity $U_f \sec \phi$ where ϕ is the angle HOA. The angle of inclination of the front BA at A must be the critical angle θ_s corresponding with the surface pressure p_s. Hence the surface velocity of A is also $U_s \sec \theta_s$. Equating the two expressions for the velocity, we have -

$$U_f \sec \phi = U_s \sec \theta_s \qquad (4)$$

Now for pressures not greater than about 20,000 psi, we have -

$$U = C_0(1 + 6.65 \times 10^{-6} p), \text{ where p is in psi}$$

Hence

$$13.3 \times 10^{-6}(p_f - p_s) = (\theta^2 - 0^2) = 13.6 \times 10^{-6} p_s - (H/R)^2$$

This gives

$$p_s = 0.495\, p_f + 3.7 \times 10^4 (H/R)^2 \text{ psi} \qquad (5)$$

The table gives some values of p_s, p_f against R for an explosion of 20,000 tons of TNT, when H = 90 ft.

R	330	600	800	1000	1500	2000	2500
p_f	20,000	10,600	7650	5890	3710	2650	2070
p_s	12,700	6080	4250	3200	1970	1390	1070
U_B	730	450	340	270	170	126	100

The angle of inclination of AB to the surface is of great importance. Here it is only possible to give an order of magnitude calculation. We assert that the rate of descent of B is $(C_f - C_s)$, where C_f and C_s are the velocities of sound at the free water pressure and at the surface pressure.

Now C in ft/sec is given at pressure p psi by

$$C = C_0(1 + 2 \times 10^{-5}p)$$

Hence

$$U_B = 0.10(p_f - p_s) \text{ ft/sec.}$$

The following conclusion would appear to have a sound foundation. Suppose that from measurements, the peak pressure in a shallow water explosion is measured as p psi near to the surface at depth G ft. For example, in Test B, p might be the pressure at 25 - 50 ft depth. Then the angle θ follows from formula (3). Now as far as the hydrodynamics of the water motion near the gauge are concerned, the pulse appears to come from a depth Rθ, where R is the radius from the center. The duration of the pulse by acoustical arguments will therefore have the value

$$\tau = 2\theta G/c = 1.4 \times 15^3 G p^{\frac{1}{2}} \text{ milliseconds}$$

This will be found to be long compared with the normal acoustical valve. An improved formula is given in a later section.

There is one extremely important consequence of the above paragraph, amounting in fact to giving an alternative position for bomb and ship to produce an identical pressure pulse, and therefore identical damage. The one uncertainty at present is that in Test B some of the damage was caused by the second pulse, arriving 0.1 sec later, and resulting undoubtedly from the presence of the bottom.

Suppose that at depth G ft at radius R ft the peak pressure was p. Then the pulse has a direction which has an angle of incidence θ. Suppose that R_f ft is the distance that the same bomb would give a free water pressure p. Then the pulse at G would be the same as that observed if the depth of bomb were $R_f \theta$ and the distance of the point G were R_f from the bomb. Take for example, the 1000 psi level which occurred at about 2600 ft in Test B. We have $R_f = 5000$ ft, $\theta = 6.65° = 0.116$ radians. The pulse from an explosion at depth 580 ft and distance 5000 ft observed at depth G would be the same as that actually produced at 2600 ft at the same depth for the field point G. As noted earlier, the argument ignores the second pulse.

Pressure-Time Curve for a Particle

The formula for the duration τ given in the previous sections was based on acoustical theory. This, of course, was an approximation; the pressure pulse at any point is only approximately a step-function. The following analysis gives the actual shape of the pressure-time curve at any point, to first order. More complicated computations will give the curve to a higher order of accuracy.

The basic idea is that in the system of reference in which the shock wave is at rest, a mass particle moves essentially at C_0, the velocity of sound at zero pressure, right through the shock and the rarefaction zone. In the region between the shock and the end of the rarefaction zone, the time taken to sweep out any angle at 0 is simply proportional to the angle, to first order. Thus if we calculate the angle subtended by any part of its path in the important region, we can immediately convert this part of the path on to a time scale. The pressure-time curve at any fixed point in space in a reference system in which the unshocked water is at rest is the same to first order as the pressure-time curve following a particle, provided the two depths are the same.

The particle enters the shock at S, and its velocity is slightly changed. It moves at constant pressure along the straight line SNA, and the rarefaction begins at A. Clearly

$$\angle SON + \angle NOA = \angle SOA$$

and $\angle SON$ is the angle θ of the shock. If p_s is the pressure in the shock, we have already proved to first order

$$\theta = 0.437\sqrt{p_s}$$

where θ is in radians and p_s is in 103 kilogrammes/cm^2 (6.56 tons/in^2).

Also, it is clear from the triangle of velocities that to the first order giving non-zero terms

$$\angle NOA = u\theta/c$$

where u is the mass velocity behind a shock in still water of pressure p. Since u/c is of first order, we neglect $\angle NOA$ compared with θ.

We have now to consider the angular rarefaction zone $\angle AOB$. Let ℓ and m be the radial and tangential velocity components respectively. Then one of the equations of motion, in the angular rarefaction zone, is

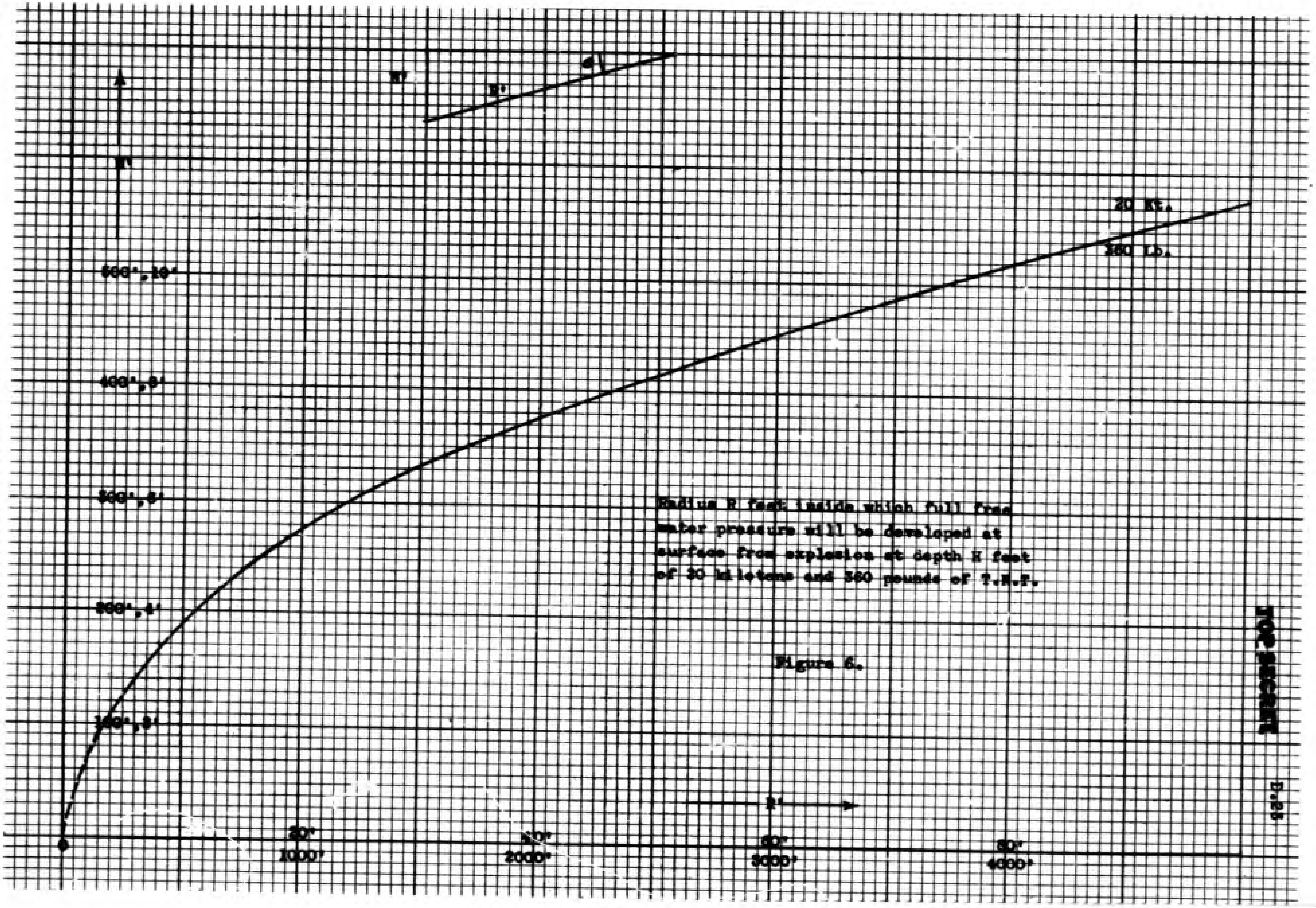
$$m = \frac{d\ell}{d\phi}$$

whose ϕ is the angular co-ordinate.

Bernouilli's equation gives

$$(\ell^2_p + m^2_p) + 2\int_0^p v\,dp = (\ell_s^2 + m_s^3) + 2\int_0^{p_s} v\,dp$$

where ℓ_p is the radial velocity component at angle ϕ, measured from OP, at which angle the pressure has fallen from the shock pressure p_s to p.



Radius R feet inside which full free water pressure will be developed at surface from explosion at depth H feet of 20 kilotons and 360 pounds of T.N.T.

Figure 6.

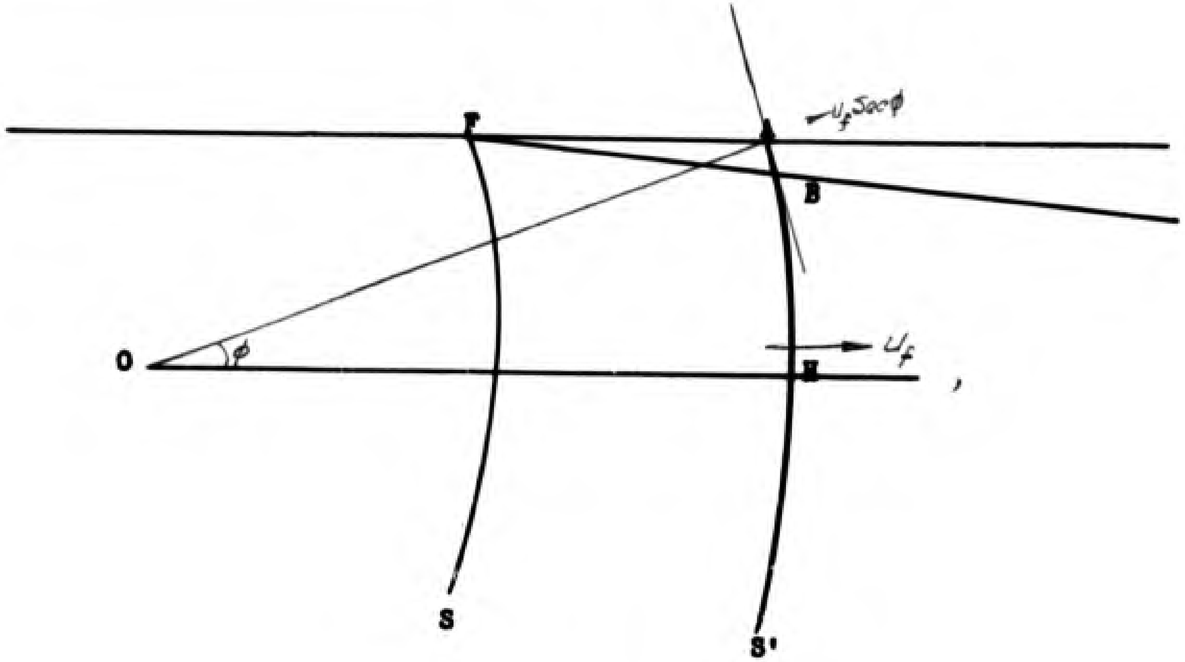


Figure 7.

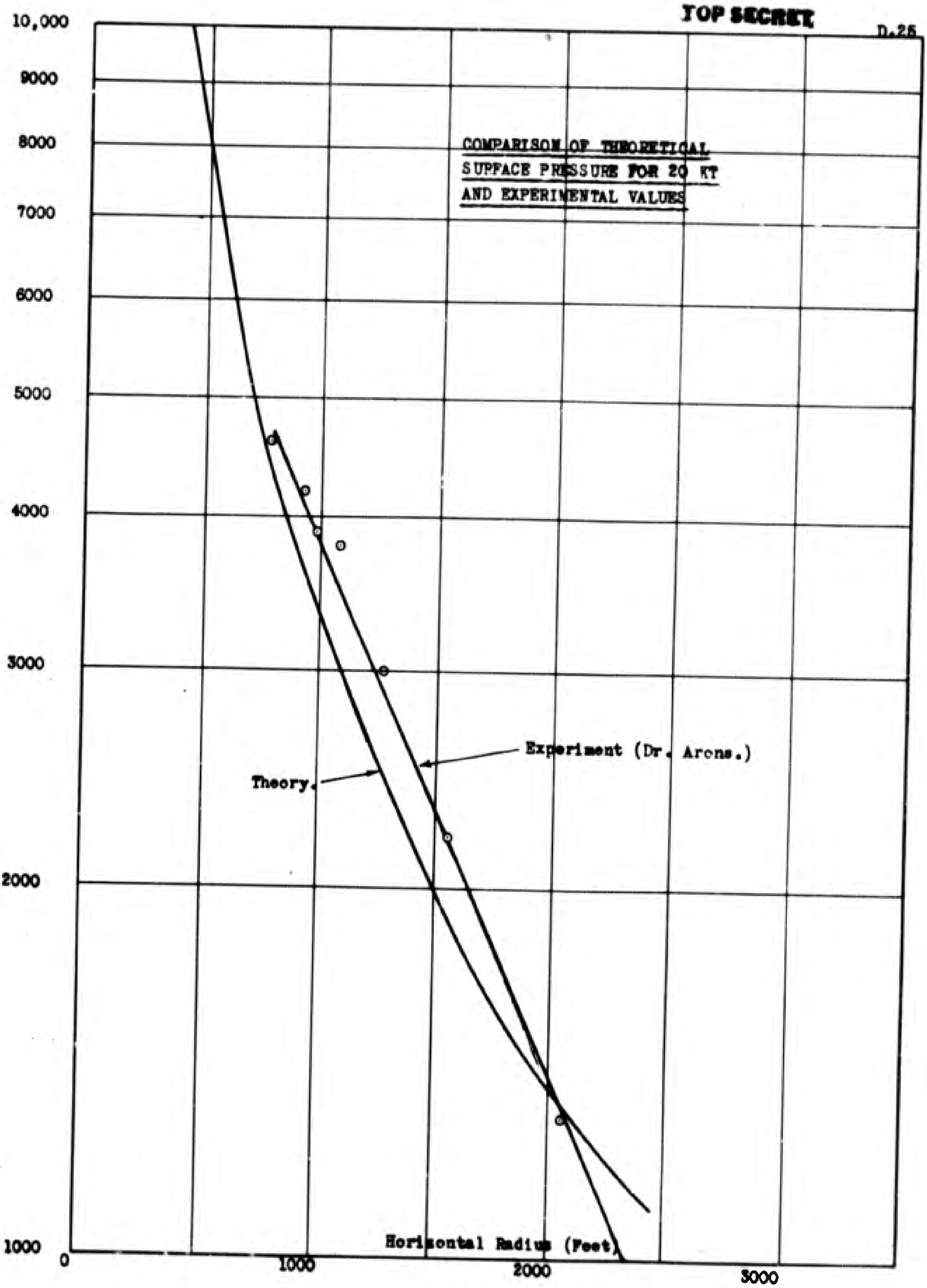

COMPARISON OF THEORETICAL SURFACE PRESSURE FOR 20 KT AND EXPERIMENTAL VALUES
10,000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1000
2000
3000
Horizontal Radius (Feet)
Theory.
Experiment (Dr. Arons.)

Figure 8.

Now

$$\ell_s^2 \qquad \begin{aligned} m_s^2 &= C_s^2 \\ m_p^2 &= C_p^2 \end{aligned}$$

and for the equation of state assumed for water, and given previously

$$\int_\alpha^\beta v\,dp = \frac{0.138}{0.862}\left(C_\beta^2 - C_\alpha^2\right) = 0.160\left(C_\beta^2 - C_\alpha^2\right)$$

Hence, Bernouilli's equation gives

$$\ell_p^2 = 1.32\left(C_s^2 - C_p^2\right) = 0.379\ Co^2\left(p_s - p\right)$$

The above equation of motion may be simplified to first order by replacing m by Co. Then we have

hence
$$\ell = 0.615\frac{d}{d\phi}\sqrt{p_s - p}$$
$$\phi = 0.615\sqrt{p_s - p}$$

The angle AOB therefore is given by

$$\angle\ AOB = 0.615\sqrt{p_s}\ ,$$

while the pressure falls off quadratically in the angular rarefraction zone.

Suppose that the pressure-time curve is measured at depth G ft, and that p is measured in psi. Then we have

(1) Region SON. Pressure equal to shock pressure

$$\text{Duration } T_1 = \tfrac{1}{2}\tau = G\,\theta\,/Co = 0.70 \times 10^{-3}\ G\sqrt{p_s}\ \text{milliseconds.}$$

(2) Region NOA. Pressure equal to shock pressure.

Duration to first order zero. To higher order

$$\text{Duration} = 2.2 \times 10^{-9}\ G\ p_s^{3/2}\ \text{milliseconds.}$$

(3) Region AOB. Pressure falls from p to zero in a time

$$T_2 = 1.42\ T_1 = 0.71\,\tau = 0.99 \times 10^{-3}\ G\sqrt{p_s}\ \text{milliseconds.}$$

Measuring time t from the point A, the pressure falls with time according to the law

$$p = p_s \left[1 - (t/T_2)^2\right]$$

The diagram shows the pressure-time curve at depth G at a point where the surface pressure is p. The curve is a universal function; the first part is a step function lasting one half of the acoustical duration for a shock incident at angle θ, and the second part is a parabolic decay, and lasts for 0.71 times the acoustical duration for a shock incident at angle θ.

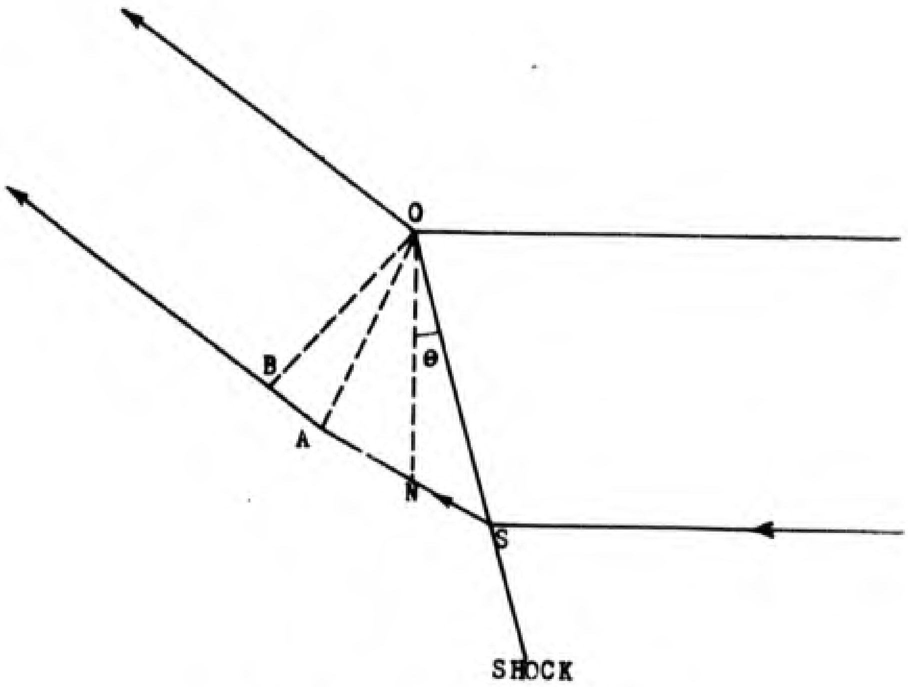


Figure 9.

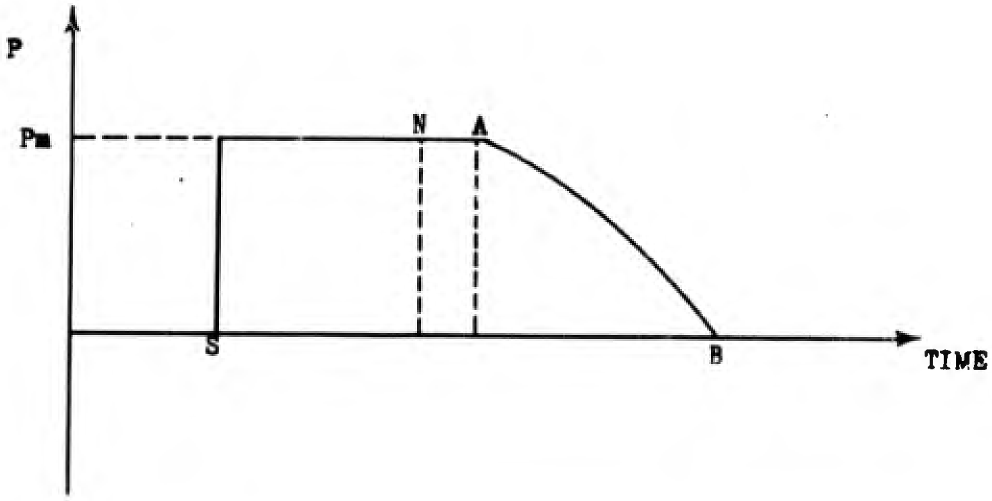


Figure 10.

TEST OF THE HYPOTHESIS DAMAGE PROPORTIONAL ENERGY IN SHOCK PULSE.

No calculation, however elaborate, could succeed in predicting all the details of damage caused to a ship by an underwater explosion. However, the severity of damage obviously decreases rapidly with distance, and it is possible to make some informed guesses on approximate distances at which various ships will experience certain broad categories of damage. In the next section, for example, we estimate the radii of damage for several depths of burst to cause the same type of damage as was produced by the Baker explosion in various ships. The hypothesis is made there that an underwater explosion pulse produces damage depending on the energy in the pulse.

The details of the shock pulse in the water near the keel of a ship, caused by an atomic bomb, vary according to the conditions, but in all cases the pulse has a step form. This is because the "cut-off" time is always considerably less than the time constant of the free water pulse. Thus our hypothesis really amounts to assuming that the damage severity is controlled by the parameter $p^2\tau$, where p is the pressure in the shock pulse, and τ is the duration, or "cut-off" time. Expressed in absolute units, the total kinetic and potential energy in the pulse crossing unit area, up to the time of cut-off, is

$$E_r = \frac{p^2\tau}{\rho c}$$

where ρ is the density and c the velocity of sound.

The present section tests the hypothesis that severity of damage is controlled by E_r, and not, for example, by a parameter such as $p\tau$, the momentum, or any other conceivable combination of p and τ .

The Test B explosion was "shallow", and the pressure pulse cannot be calculated by the ordinary "cut-off" theory. One can use the theoretical relationship for τ namely

$$\tau = 1.4 \times 10^{-3} \, G \quad \sqrt{P} \quad \text{milliseconds}$$

for the duration of the pulse at depth G feet at the points at which the shock pressure is p psi. Using this relationship to substitute in the formula for E_T, and expressing the result in units foot pounds per square foot, we get

$$E_T = 3.0 \times 10^{-6} \, G \, p^{5}/2$$

The following table shows the results for 8 ships. Two points on the keel of each ship have been taken, one the nearest point of the keel to the explosion center, and the other the mid-point of the keel to the explosion center. In the case of the submarines PILOTFISH, APOGON, and SKIPJACK, all submerged with little positive buoyancy, very small leaks were sufficient to cause sinking.

Ship	Keel G feet	p psi N.P.	p psi M.P.	E_r N.P. x 10-4	E_r M.P. x 10-4	Remarks
ARKANSAS	30	5000	4650	16.0	13.0	Many plates ruptured
SARATOGA	32	3500	3300	6.9	6.0	Some plates seriously dished. Information scanty.
PILOTFISH	40	4700	4150	18.0	13.4	Pressure hull dished and torn.
APOGON	90	1050	980	0.97	0.81	Some damage to pressure hull.
SKIPJACK	45	1100	1100	0.54	0.54	Considerable damage to pressure hull.
FALLON	14	2600	2100	1.45	0.84	Plates dished but not ruptured.
HUGHES	16	1570	1570	0.47	0.47	Slight dishing. Little hull damage
Y.O. 160	25	3050	2450	3.83	2.22	Sunk. Never reappeared from water column.
LST 133	6	1600	1450	0.19	0.14	Little structural damage. No plate damage.
GASCONADE	14	1800	1550	0.58	0.40	Plates dished but not ruptured.

N.P. means nearest point; M.P. means mid point.

ARKANSAS was left upside down on the bottom. Extensive heavy damage to plates was to be found everywhere over the sides and bottom. SARATOGA showed some dishing of plates, but the ship sank upright; and no information is known about the plates at the bottom. It is most likely that many were ruptured. PILOTFISH showed heavy damage to the pressure hull; PILOTFISH was a modern heavy hull submarine. APOGON also was of the heavy hull type, and showed dishing of plates and some failure of frames. SKIPJACK was of light hull construction, and the hull was dished considerably. No information has been obtained on Y.O. 160. The other ships in the table are covered sufficiently by the details given in the table.

Certain inconsistencies appear in the above table. For example, the fact that the FALLON, although damaged and leaking, did not sink, while the submarines APOGON and SKIPJACK did sink, is slightly puzzling. Of course, all of the mechanical variables of the shock pulse used in constructing the table are subject to slight uncertainty. Furthermore, the reflected pulse off the bottom may have caused some of the damage, the reflected pulse was irregular due to variations in the bottom. Again, a large intake of water is required to sink a surface ship, but very little is required to sink a submarine submerged with only a few tons of positive buoyancy.

The results, show quite clearly that the degree of damage depends both on peak pressure and depth (or what amounts to the same thing, duration). The degree of damage is about equally well described as proportional either to

$(\text{pressure})^2$ x duration, which is energy

or pressure x duration, which is momentum.

Of these 2 criteria, the first is preferred for mechanical reasons.

There is one remark which can be made on the above table of results, directed towards explaining the survival of the FALLON with its energy value 1.45 and the sinking of the APOGON with its energy value 0.97.

It is a well-known phenomenon in the theory of sound that the reflection of a pulse at a rigid wall gives a reflected wave of equal strength, so that the pressure acting on the wall reaches a value twice that in the original pulse. The suggestion is made that it is this simple fact which gives the underlying principle accounting for the survival of the FALLON. The underwater pulse in the Test B explosion, acting on the ships, lasted one or two milliseconds. Since the speed of propagation was about 5000 ft/sec, the length of the pulse up to the time of cut-off was between 5 and 10 ft. Hence, if the projected area of the side of a ship in the direction of the movement of the blast wave had a minimum length of about 10 ft, the central regions of this area re-acted to the shock pulse as if they were part of an infinite wall. In other words, there was no relieving pulse reaching the region considered, coming from the free water below the ship or at the two ends.

According to the theory of sound, the doubling by reflection at a rigid surface is independent of the angle of incidence. However, if the reflecting surface deforms, then the angle of incidence definitely affects the results. It is perhaps too naïve to suggest that for normal incidence the total energy of the pulse, both kinetic and potential, are available for causing deformation, while for grazing incidence only the potential energy is available, but this description has an underlying principle of truth.

Referring to the map of the Test B explosion it will be seen that the FALLON was pointing almost directly at the explosion while APOGON and SKIPJACK, like most of the other ships were broadside on. Since the shock pulse had a front which was nearly vertical, the pulse swept across the bottom of all ships at almost grazing incidence.

An inspection of the table suggests that:

(1) any capital ship will be sunk by a value $E_T = 10^5$ ft. lb./ft.^{2}.

(2) any capital ship will be seriously damaged by E_T x 5 x 10^4, but will not sink from rupture of plates. Some danger of sinking will arise from fractured pipes.

(3) lighter ships, such as destroyers, transports and merchant ships will probably be sunk with a value 2 x 10^4.

(4) submarines will probably be sunk by $E_T = 10^4$, unless leaks, not through the main pressure hull, but through hatches and fractured pipes, can be stopped.

(5) ships pointing towards or away from a shallow explosion will not be damaged as heavily as ships at other angles, particularly broadside-on, at equal distances.

The pressure-time curves in Test B obtained with the Hilliar gauges agree surprisingly well with the theoretical results just described. Near to the center the experimental results indicate higher pressures and slightly shorter duration, but further out the agreement is nearly perfect, and is in fact much better than would be anticipated from the approximate nature of the theory.

Energy in the Pulse.

The approximation has previously been made that the energy in the positive pulse was that of a square acoustical pulse of pressure p_s and duration τ.

$$W = \tau p_s^2/\rho c$$

The calculations given above, show that the energy is more closely approximated by

$$W = (0.5\ \tau p_s^2/\rho c) + (0.71\ \tau p_s^2/\rho c) \int_0^1 (1-x^2)^2 dx$$
$$= 0.88\ \tau p_s^2/\rho c$$

Therefore the numerical results given previously and based on the acoustical duration need a small correction, but the magnitude of the correction is only 12%, and there is little point in applying it, in view of the other uncertainties involved.

Reflection of Shock Pulses at More Normal Angles of Incidence.

The classical experiments of Hilliar, and many similar measurements made to confirm his views, have shown that the image theory of the reflection of a shock wave in water at a free surface represents the facts. The theory put forward now indicates that the "cut-off" pulse has a fine structure at the edge. It is easy to show by the methods used above that, for a shock pulse of very long decay time, the angle of reflection equals the angle of incidence but only to the extent of a first approximation. Higher order terms, of increasing importance the higher the shock pressure, slightly modify the result. The angular rarefaction zone, in which the pressure drops away from p_s quadrically with time, is very narrow compared with the zone in which the pressure is p_s. The details can be worked out, and make an interesting mathematical exercise, but they can be applied only to the pulse very near to the surface with an ordinary explosion (1 lb. - 1000 lb.) because the theory given is based on the hypothesis that the time constant of the pulse is large compared with the duration of the "cut-off" pulse. Lengthy numerical calculations probably offer the only hope of discovering the nature of the solution when the time-constant of the shock pulse is also to be introduced with the analysis.

Explosions at Greater Depths.

An attempt is made in the following sections to estimate the effect of placing the bomb at greater depths in deep water. First, an estimate of the largest wave system is made and the conclusion here is that the greatest waves are produced when the bomb is 400-500 ft deep. The main problem to be considered, however, is to calculate the radii at which various ships would be damaged to the same degree as they were in Test B if the bomb were exploded at various depths. In order to do this, the hypothesis was proposed and tested in the previous paragraphs that the damage depends on the energy in the shock pulse up to the time of cut-off. The agreement with the results was fairly satisfactory. Applying the hypothesis to ships of about the same structural strength as **ARKANSAS** and **SARATOGA**, it appears that the greatest radius of sinking is about 800 yd, and that this is achieved with any depth of burst between 600 ft and 1200 ft.

Greatest Waves Obtainable from an Atomic Bomb Explosion in Deep Water.

The waves from an explosion in deep water are greatest when the depth of the charge is about 0.8 times the radius of the bubble caused by the explosion. The effect of the explosion is to make a large cavity, the top of which breaks and lets in air when the cavity is greatest.

At this instant the water everywhere, except that in the dome, is approximately at rest. The waves are generated from the collapse of the cavity under the hydrostatic forces due to gravity.

Assuming that the bomb is equivalent in "bubble forming" power to 20,000 tons of TNT an assumption which must be reasonably justified but may nevertheless be wrong by ± 25%, the greatest waves will be generated from an explosion at depth 450 ft. To estimate the waves, we use the laws proposed by the writer in Index 119, and tested experimentally by Bryant in Index 166. Bryant used a charge 32 lb, exploded at 8 ft depth in fairly deep water. We are now considering 20,000 tons at 450 ft depth. If R_2 is the radius of the large bubble and R_1 is the radius of the 32 lb bubble at 8 ft (known experimentally to be about 11 ft), we have

$$\frac{R_2^3\ (450 + Z)}{R_1^3\ (8 + Z)} = \frac{20000 \times 2240}{32}$$

where $Z = 34$ ft, is the head of water corresponding with atmospheric pressure. Solving this equation

$$R_2/R_1 = 48,$$

so that the atomic bomb bubble radius, when the depth of explosion is 450 ft, is about 550 ft.

The measurements of the waves made by Bryant on the 32 lb charge at 8 ft depth, were taken at distance 56.5 ft. These now may be scaled to the atomic bomb at 450 ft depth. Wave heights must be increased by a factor 48, and the waves will be those at distance 2700 ft. The second large wave will be the highest, and this will be preceded by the deepest trough. The maximum trough to crest height will be 90 ft, and the period of the wave will be 19 sec, corresponding with a "wave length" of about 1900 ft. Hence the waves will be rather steep but not breaking at 2700 ft radius. Further out, the waves will be comparatively harmless to ships, but might be serious if there were any shore installations on a nearby beach, such as there would have been at Bikini Atoll in Test C.

Bryant made an approximate interpretation of the shape of the cavity caused by the explosion. Figure 12 shows the estimated cavity shape, and the waves at 2700 ft radius from an atomic bomb exploded at 450 ft depth.

Bomb positions to give equal damage

Reasons have been advanced for supposing that the damage to a given ship by a step-pulse of pressure p and duration t is proportional to p^2. Let G be the draught of the ship and c the velocity of the wave; we neglect the small variation of c with p. Then if the theory given is valid,

$$p^2 \tau = \frac{2G p_f}{c} \left[(R/H)^2 + 1 \right]^{-\frac{1}{2}} \qquad (1)$$

where R is the horizontal distance of the bomb, H its depth, and pf is the free-water pressure pulse at a radial distance $(H^2 + R^2)^{\frac{1}{2}}$.

It is shown in the volume on "Water Blast" that this theory is valid only if

$$H > R\theta \ (p_f) \qquad (2)$$

where

$$\theta \ (p) = 3.60 \times 10^{-3} p^{\frac{1}{2}} \qquad (3)$$

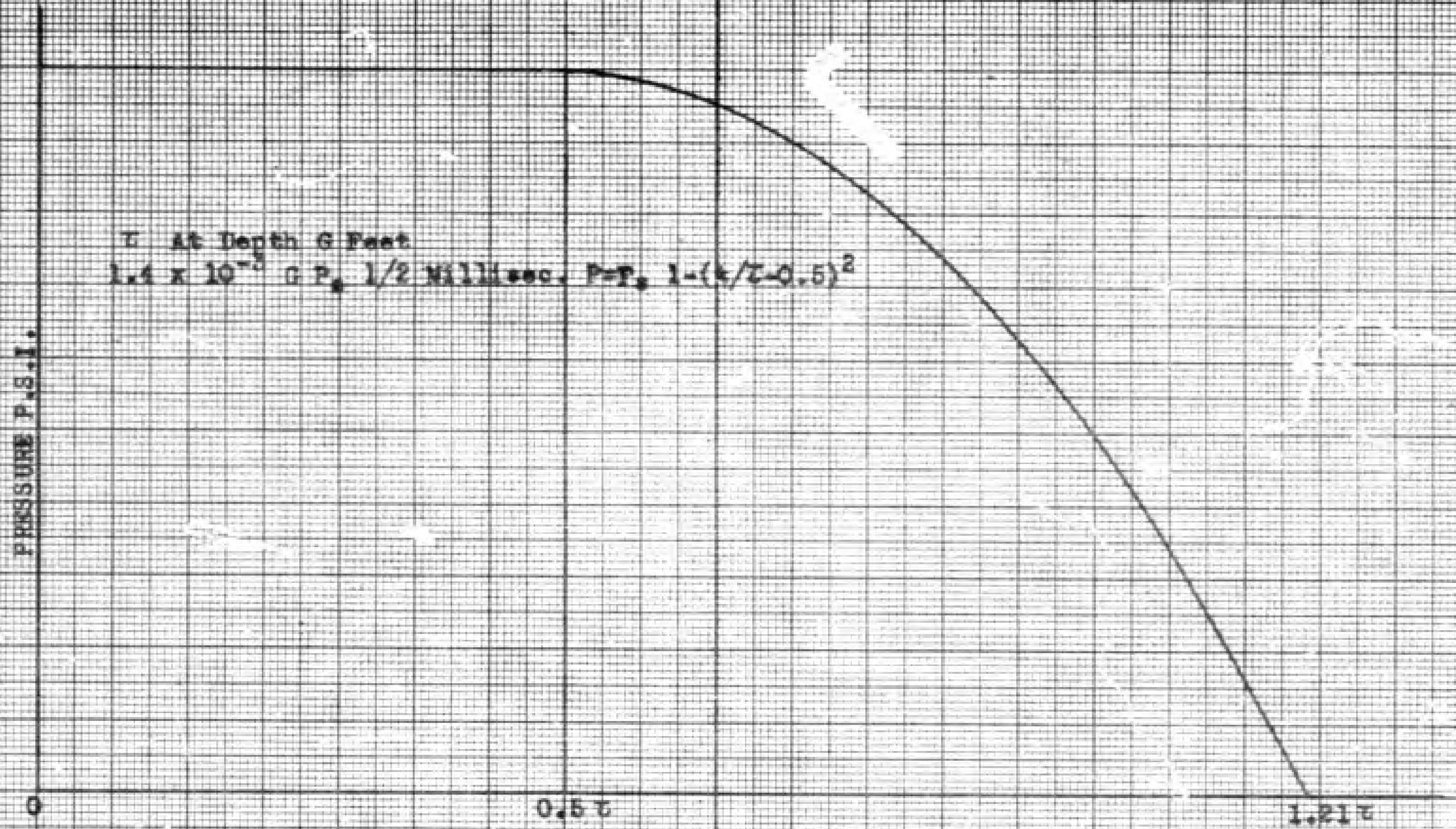
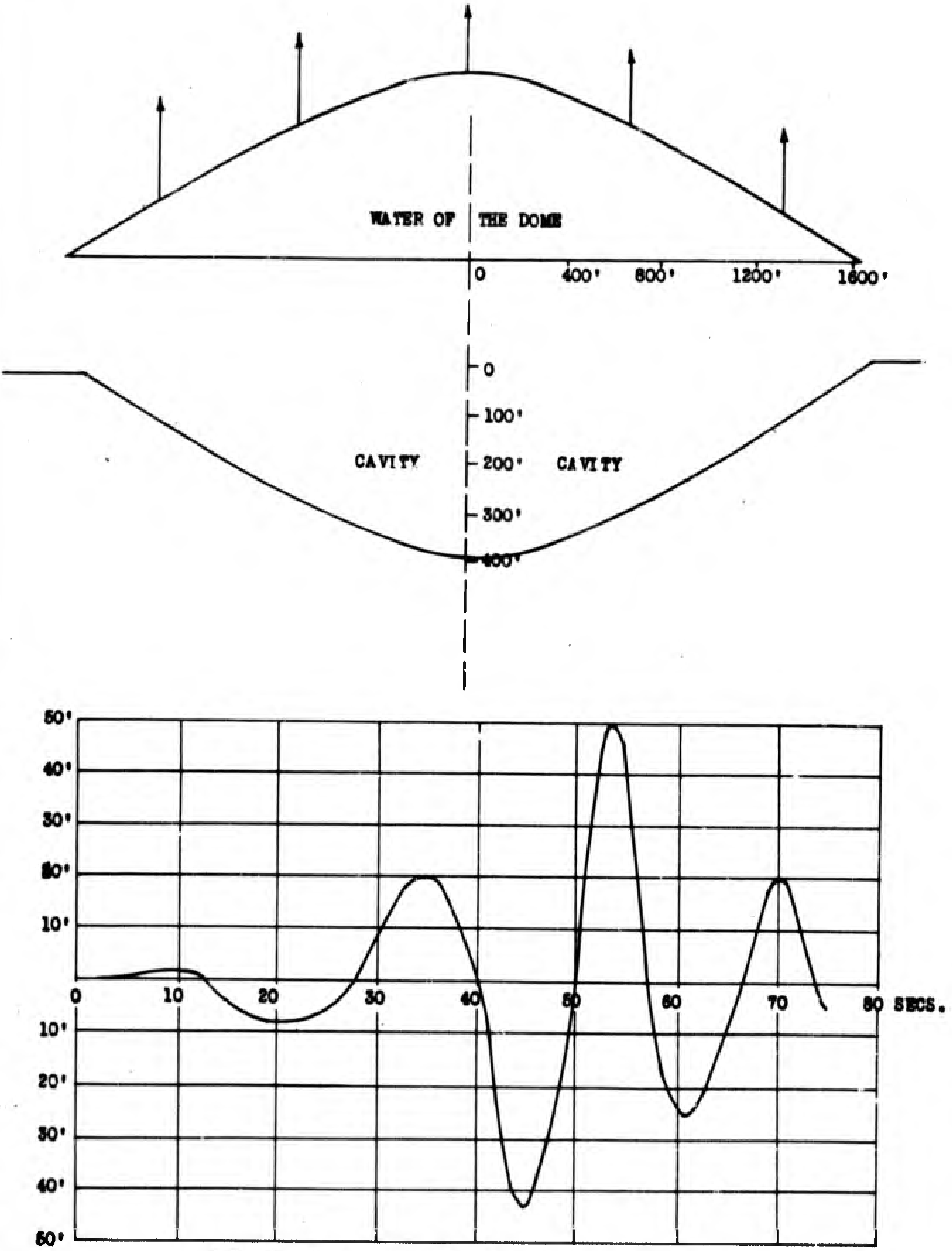

τ At Depth G Feet
1.4×10^{-3} G P_s 1/2 Millisec. $P = P_s$ $1-(t/\tau-0.5)^2$
PRESSURE P.S.I.
0
0.5 τ
1.21 τ

Figure 11.



WAVE HEIGHT AT 2400' FROM BOMB AT DEPTH 450'.

Figure 12.

if p is in psi. If (2) is not satisfied, then

$$p^2 \tau = \frac{2G}{C} p_s^2 \, \theta \, (p_s) \tag{4}$$

where the surface pressure p_s is approximately

$$p_s = 0.495 \, p_f + 3.7 \times 10^4 \, (H/R)^2 \text{ psi} \tag{5}$$

The following diagram was calculated from these equations. The function p_f was taken from the Crossroads Handbook for an explosion of 20 kilotons TNT. A set of bomb positions is shown, for which constant damage would be inflicted on a ship by the first pulse only. The approximate theory, in the region where the Meyer solution is not valid, does not fit exactly on to the curves from the acoustic theory, but the difference is never large. To eliminate the gap, one would have to consider the rate of fall, through the water, of the boundary where the Meyer solution fails. The transition curves would then depend on the draught of the ship. This is the only place where the curves of constant damage are affected by the draught. The extent of the constant damage suffered by a given ship does, of course, depend on the draught.

In so far as the energy $p^2 \tau$ is not an exact criterion of damage, the curves cannot be said to have any precise definition. However, there is little doubt that as far as planning purposes are concerned, the curves are adequate.

It will be seen from the figure, that the optimum depth for the bomb to cause the same damage to SARATOGA as was inflicted by Bomb B is calculated to be 1700 ft. The calculated horizontal radius is 830 yd, compared with 380 yd in Test B.

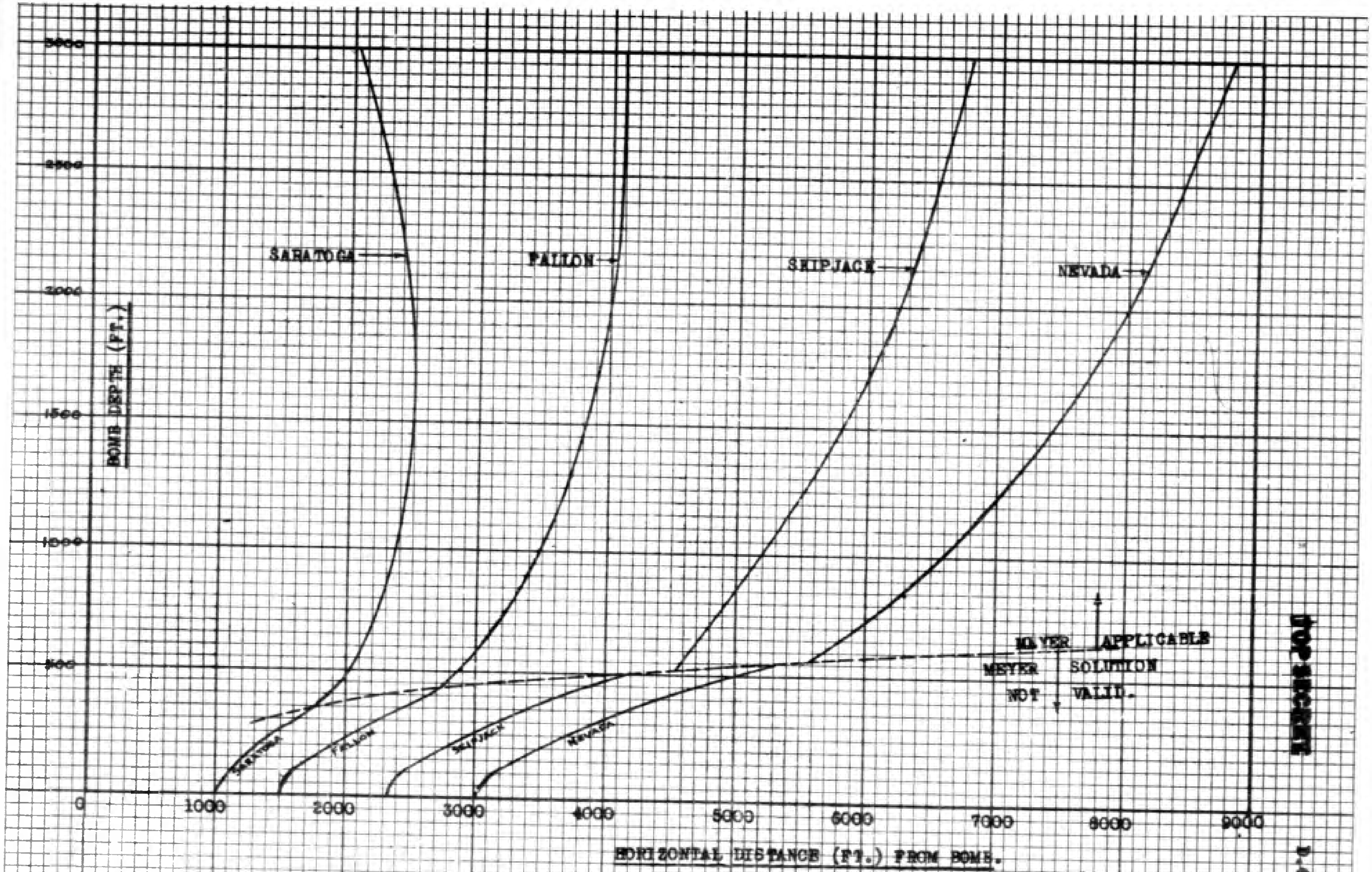


Figure 13.

BOMB POSITIONS TO GIVE CONSTANT DAMAGE IN FIRST PULSE

THE STRUCTURE OF THE WATER SPOUT

The structure of the spout from a shallow water explosion is of great practical importance and considerable scientific interest. The importance lies in the fact that the radioactive fission products are dissolved in the water droplets of the spout. Since most of the droplets fall back to the surface of the sea within a period of time measured in hours, a study of the problems of the contamination of the area surrounding the explosion hinges on obtaining an understanding of the mechanics of the formation of the spout. One must consider for example, whether a contact explosion, or an explosion 20 or 30 ft above the sea, would form a spout. If not, then most of the fission products would not become attached to water droplets and would, therefore, presumably be carried into the upper atmosphere and escape.

The water spout is an interesting problem mechanically for a variety of reasons. In the first place, the diameter of the spout appears to scale for a range of explosive charges as large as one million-fold. The height of the spout scales very well for charges ranging from a few ounces up to a few hundred pounds. At this point, the effect of gravity begins to count and large charges do not give spouts relatively as high as small charges, i.e. when expressed in terms of a scaled length. The amount of water contained in the spout is not known although many speculative estimates have been made. For example, in the case of Test B, the radius of the spout was about 900 ft and the depth of the water was 180 ft. If one assumes that the whole of the water inside a cylinder of radius 900 ft was thrown upwards into the air to make the spout, then the total amount of water in the spout was about 12 million tons. Based on this simple calculation, statements have been made that the amount of water thrown into the air was between 1 and 10 million tons; such a statement is to be found in the report of the President's Evaluation Committee. It is thought that these figures are seriously over-estimated by a factor lying between 10 and 100. For reasons which will be explained later, it is considered much more likely that the amount of water thrown into the water spout, including the cloud at the top, was about 50,000 tons.

Conventional Theory of the Motion of the Surface

According to the theory of sound, the mass velocity of the water particles at the shock wave front is given by

$$u = p/\rho c$$

where p is the shock wave pressure, ρ is the density and c is the velocity of sound. Thus, for example, the mass velocity is 14.5 ft/sec when the shock wave pressure is 1000 psi.

When a shock wave reaches a free surface at normal incidence, the pressure falls to zero and the mass velocity doubles. If the shock wave reaches the surface at an angle of incidence $(\pi/2 - \theta)$ then the impulsive velocity given to the free surface is

$$v = 2p \sin\theta / \rho c$$

Consider now the conditions applying at the edge of the water spout in Test B. The shock pressure given by the experimental results was 4000 psi. According to the theory developed earlier, the angle θ was 13°; therefore, the impulsive upward velocity given by the shock was on 26 ft/sec.

Neglecting air resistance, this would take the water only to a height of 11 ft. From the photographs of the water spout, it will be seen that there is a very large fringe to the spout extending considerably beyond 900 ft radius. It seems likely that the fringe is caused by the shock wave. On the other hand, it is clear that the shock wave at the outer regions of the water spout is not responsible for throwing the water high up into the air and thus accounting for the spout. Even when one remembers that the water surface is unstable when it is shocked impulsively upwards, so that ripples are greatly magnified, it in inconceivable that the shock at 900 ft radius could throw water more than 30 ft into the air.

"Afterflow Motion"

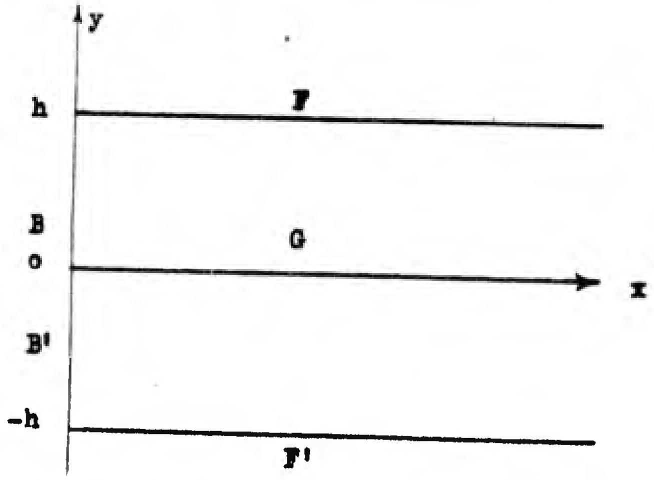
As is well-known, an explosion in water at a depth at least several bubble radii separates into two phases. At any point in the water, the first disturbance to arrive is the shock wave. This quickly passes, and is succeeded by the "afterflow". This phase is practically identical with that which would be achieved by the gas bubble pulsating in an incompressible liquid. The particle velocity at any point is inversely proportional to the distance from the center, while the pressure and mass velocity at any point in the water are considerably less than they were in the shock wave phase.

In the case of a shallow water explosion, the same type of breakdown of the motion into two phases may be envisaged. The development of the bubble, its venting, and the phenomena which follow, such as wave formation, are therefore part of the "afterflow" phenomena, and for these the fact that water is not entirely "incompressible" is largely immaterial.

We must now consider the possibility that the water spout is an "afterflow" phenomenon. Idealizing the problem drastically, but at least preserving the fundamentals, we consider a sheet of water, of uniform depth, bounded at one edge by a vertical wall. Initially everything is at rest; suddenly the wall is given an impulsive horizontal velocity. Clearly the water near the wall is flung upwards.

The wall in the explosion application is represented by the sides of the bubble, before and after it has vented. The question is, does the push of the explosion on the sides of the bubble make the water further out squirt upwards with high velocity?

The complete solution of the sheet of water jerked into motion by the impulsive velocity of a vertical barrier is too difficult to solve, but at least one can calculate the initial velocity distribution of the water.



For simplicity, we imagine the ground G removed and another sheet of water added below. Then G is a plane of symmetry, while F and F' are free surfaces. The bubble surface is represented by a wall B extending from 0 to +h along the y-axis, and the image system B' extends from 0 to -h along the y axis.

A fundamental solution is

$$\phi = e^{-kx} \cos ky, \quad hk = (2n+1)\pi/2$$

Hence, the velocity potential for any arbitrary impulsive pressure over the wall, is

$$\phi = \Sigma_n A_n e^{-(2n+1)\pi x/2h} \cos (2n+1)\pi y/2h$$

The initial vertical velocity of the free surface is therefore

$$v = \Sigma \left[(2n+1)\pi A_n/2h\right] e^{-(2n+1)\pi x/2h}$$

Thus the initial vertical velocity decreases very rapidly with x. Even for the most slowly varying component, the velocity decreases e-fold in a distance

$$x = 2h/\pi$$

In one case h = 180 feet, so that the distance is 115 feet.

Let us consider the simplest case in which the initial velocity distribution conforms to the law

$$u = u_0 \cos \pi y/2h$$

This law correctly takes into account that the impulsive pressure is zero at the free surface, as it must be in our case. Then

$$A_0 = 2hu_0/\pi,$$

and the maximum upward velocity is at the point (0,h), with a value

$$v = u_0$$

We see that a pressure at the wall B cannot cause an upwards velocity greater than the maximum horizontal velocity, and that the upward velocity in any case decreases repidly as we go to distances of the order the depth away from the wall.

Now the "afterflow" velocities are considerably less than the shock wave velocities, and these were small at radius 900 ft. We conclude that the spout is not caused by "afterflow". On the other hand, the afterflow is capable of explaining the formation of waves, by the "tidal bore" mechanism already given by the writer, and in the case of explosives in earth, is capable of explaining the formation of a crater.

The Suggested Method for Which the Spout is Formed

Reasons have been given above indicating that the water in the outer parts of the spout do not rise vertically from the lagoon. By a reductio ad absurdum argument, therefore, the water in the spout must have originated near to the center of the explosion. The spout is not solid water; on the contrary it is a fine mist and the proportion of water to air by volume probably does not exceed one part per hundred thousand.

The diagrams illustrate the writer's idea on the formation of the spout. Four stages are shown and the diagrams should be self explanatory.

The question now must be asked whether an explosion at the surface of the sea would throw a large amount of spray high into the air and thus cause intense contamination over a wide area by means of a fine rain. This question is extremely difficult to answer with confidence and probably the only method of obtaining the answer, short of using another bomb, is to make a number of model experiments. In the first place it would be interesting to fire a small charge in a cavity, the walls of which were either metal or clay and if the explosion would give a spout. For example, if the radius of the charge were one, then the diameter of the cavity should be about three and the depth of the cavity should be about two. The spray should be thrown sideways and upwards giving a general appearance the same as that at Bikini with the diameter of the spout about 20.

Other experiments should be made to see what happens with a contact explosion. In interpreting the results, of course, one must pay careful attention to the fact that gravity will have a very different effect on the small scale and on the large scale. The best estimate that can be made at present is that the heat of the atomic bomb exploded at the surface will evaporate several thousand tons of water and will throw considerable amount of spray into the air. However, it is not expected that anything comparable with the spout and steam cloud observed at Bikini would be obtained.

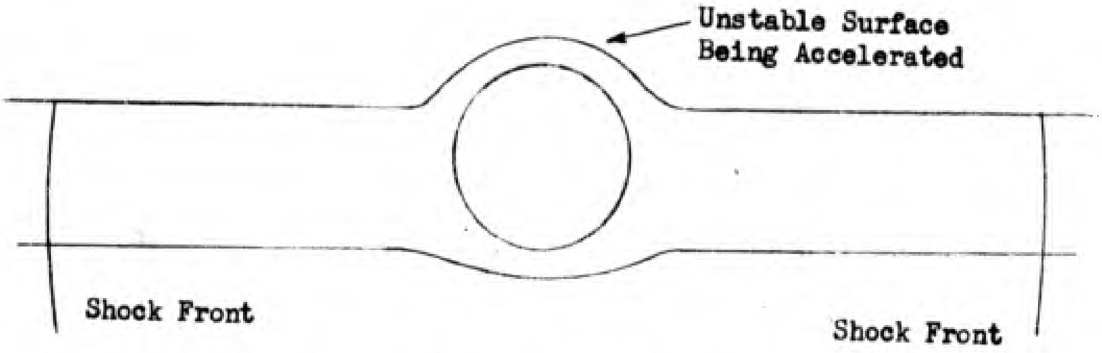
The Base Surge.

One of the remarkable features of the B explosion was the moisture cloud which appeared to spread from the bottom of the spout after the "Wilson cloud chamber" condensation fog had practically vanished. This particular cloud had not been anticipated, but there seems to be little doubt about the general lines of the explanation. The proposal is made that the cloud is caused by the spilling over of the steam and air in the spout, as the whole of the spout begins to fall. The basal moisture cloud is in fact the "spout" in another guise. The fourth diagram of the series describing the water spout illustrates the suggestions.

At the time when the Wilson fog was re-evaporated, the misty mixture of air and water in the spout and the clouds above were approximately at rest everywhere. However, the system was not in mechanical equilibrium with the atmosphere. The weight of the suspended water droplets gradually causes a downward motion to start; from the clouds indeed, rain began to fall; but in the spout there were vast numbers of minute droplets, and, as they fell, they entrained the air and water vapour near them so that the whole contents of the spout began to fall. At the surface of the sea most of the mixture was deflected sideways, although no doubt the largest water drops fell into the sea.

A mathematical theory of the falling motion of the contents of the spout can certainly be developed. The experimental information to be used in conjunction with such a theory are graphs giving the width and height of the column as functions of time. Without attempting such an analysis here, it is however clear that the basal moisture cloud must be highly radioactive. Most of the fission products were probably in the clouds above, but possibly 2 - 20% are left in the spout, and these were all carried down near the sea as the spout collapsed and became transformed into the basal moisture cloud.

Stage 1



Bubble Just Before Venting

Stage 2

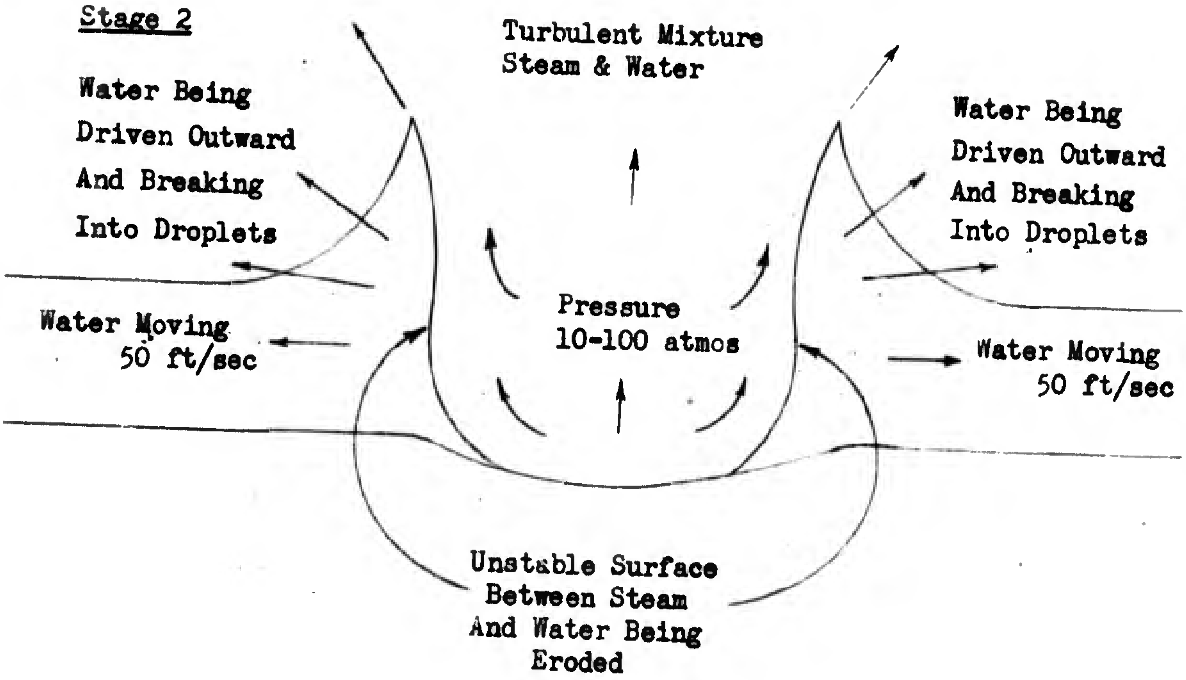
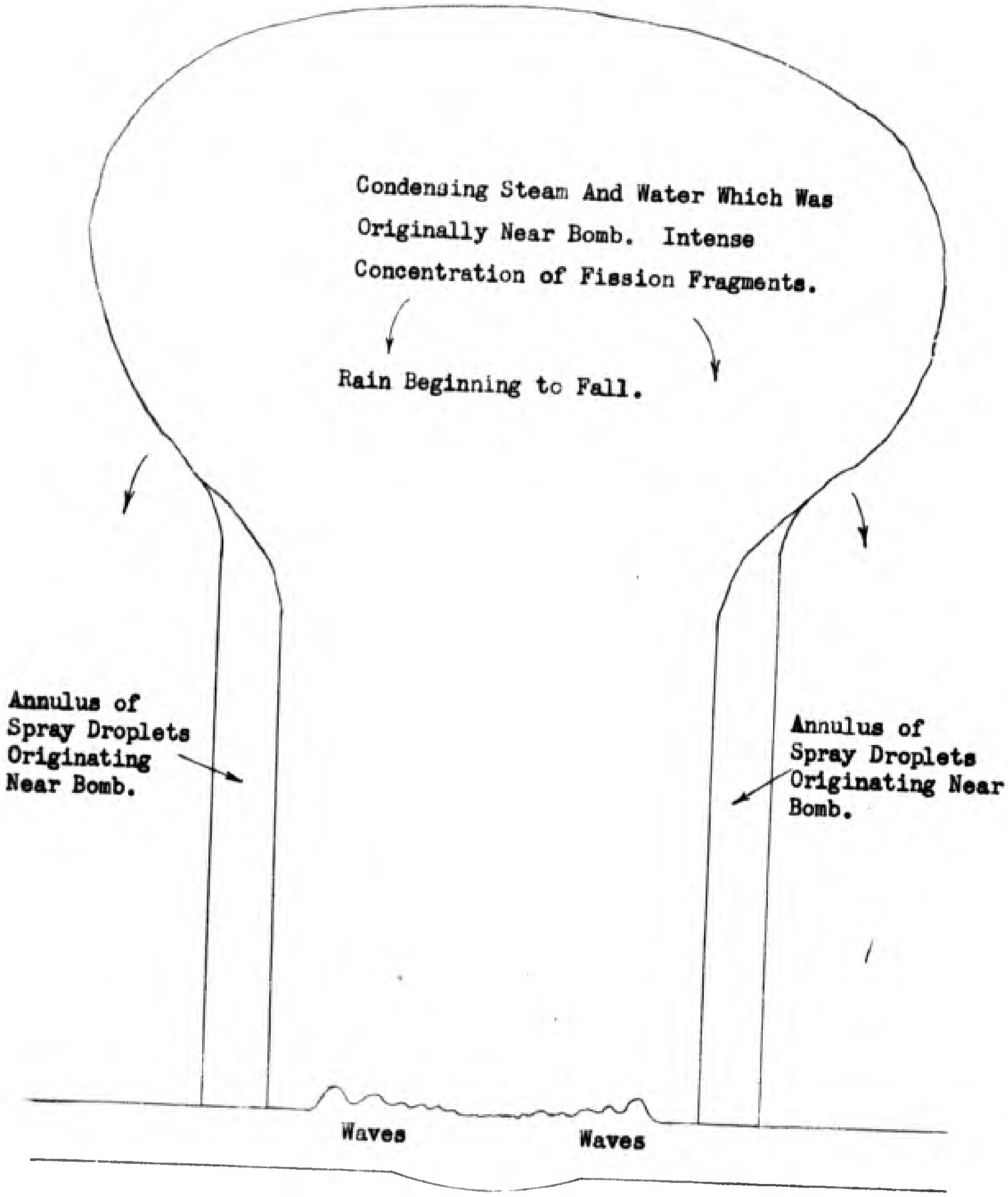


Figure 14

Stage 3



Limiting Volume Of Steam And Water Droplets After Venting. Pressure Everywhere Atmospheric.

Figure 15

Stage 4

Metamorphosis Of The Spout Into The Basal Surge

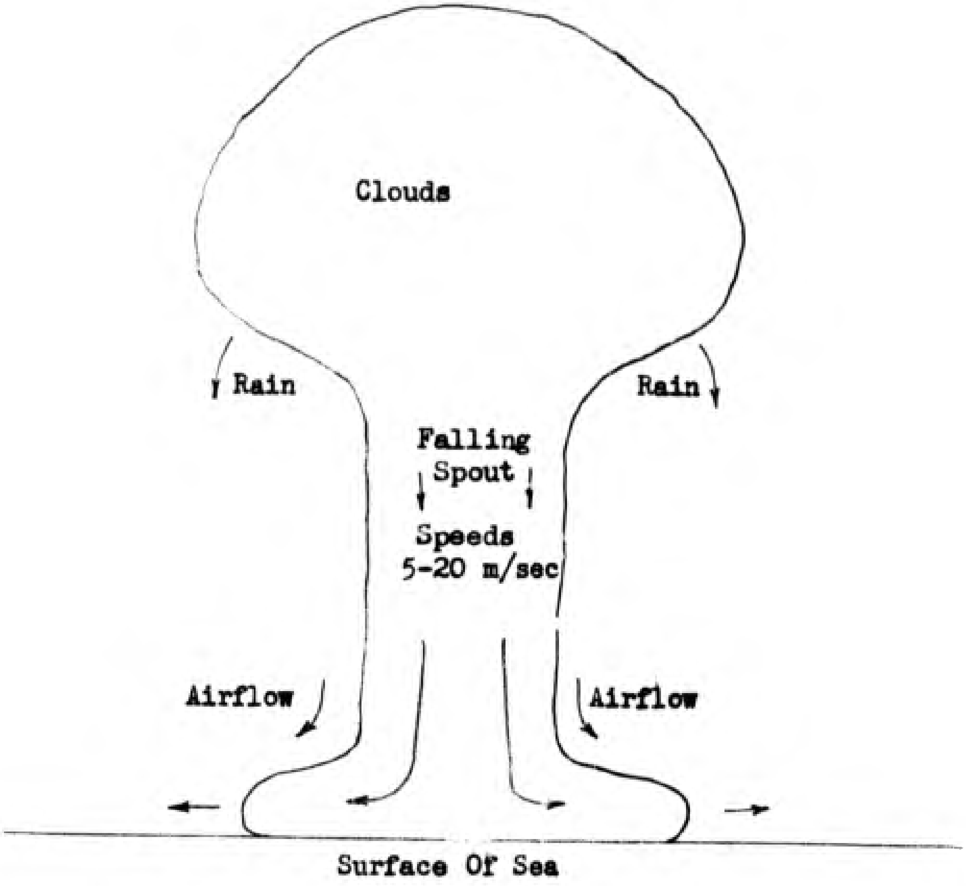


Figure 16

SECRET

ENCLOSURE E

"Report on Ship Instrumentation Other Than Air Blast and Underwater Pressure"

by

Cdr. C.H. Gerlach

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Report on Ship Instrumentation Other Than Air Blast and Underwater Pressure

In Operation Crossroads, the Ship and Instrumentation Program undertook to determine the blast and underwater pressure, to measure the properties of the explosion which imposed a loading on the structure of the target vessels, and to measure the properties of the structural response to this loading. It was expected that the response of the vessels would take two principal forms, (1) deformation of ship structure directly exposed to the shock wave, and (2) shock excitation of structure and equipment which would not necessarily involve structural deformation.

The majority of the installations were concentrated on APA's and DD's since these were the simplest target structures. Less elaborate installations were provided on the major target vessels, so that when a pattern of response had been established on the APA's and DD's, a few additional measurements would enable a response to be fitted into the pattern. It should be clearly understood that it was not the purpose of the installations to provide a formal study in structural analysis.

Identical instruments were concentrated on two APA's and two DD's. From these original installations, selected instrumentation was put on the remainder of the DD's and APA's. Thus the plan provided for detailed observation of two vessels of each type, at different distances, plus a connecting thread of reduced covering throughout the target array.

On the two APA's and DD's which were the cornerstone of the instrumentation plan, the instruments were installed in three transverse belts--a bret forward, one amidships, and one aft. In each of these brets the instrumentation was substantially the same. It provided for gauges extending from the keel out to--and up either side of the vessels. In addition to documenting the response of the structure to the direct impact of the loading, it would serve to indicate how the disturbance was transmitted through the structure.

In the DD's where there was a more extensive background of experience related to shock response, a serious effort was made to place instruments on equipment as well as on structures.

Time records of impulsive velocity were obtained by a velocity meter whose signal was recorded on two types of recorders. The velocity meter consists essentially of a seismic element surrounded by a coil, which is part of the frame. As the frame - and hence, the structure - moves, the lines of the flux of the energized coil cut across the seismic element, inducing a voltage in the latter which is proportional to the instantaneous velocity with which the frame is moving. This voltage is picked off, amplified and recorded.

In order to record the low frequency part of the velocity-time function, it was necessary to use a carrier, modulated by the velocity meter output. Two alternative systems were developed, and both were used. One consisted of a frequency modulation scheme, the other of amplitude modulation.

Peak values of impulsive velocity were determined by a gauge especially developed for the Tests. The gauge consists of a clamped circular diaphragm. The diaphragm is made of lead; the mounting is attached to the structure to be studied, and if the structure moves impulsively, the diaphragm will be left with a deflection which is a function of the maximum value of the impulsive velocity. These gauges were installed to back up the velocity meters, and being simple, were installed in quantity.

Accelerations were measured by two types of gauges - mass-plug accelerometer and the so-called putty gauge. The mass plug accelerometer consists essentially of a bakelite tensile specimen, one end of which is mounted to the structure, while the other end is free except for being guided to allow only a single degree of freedom, and loaded with a mass. By controlling the mass of the loading on the free end of the specimen, and the diameter of the specimen, a value of acceleration at which the specimen will break may be determined. These gauges were installed in groups; so that by observing the last broken specimen the value of acceleration could be delimited between two selected values.

The putty gauge consists of a graded series of spring loaded masses, so that each element will start to move at a selected acceleration. When an element moves, it is made to indent a bit of plasticine or other similar material. By observing the last indentation, the value of acceleration is bracketed.

A mechanical gauge whose record may be interpreted in terms of the nature of the disturbing excitation is the reed gauge. This consists of a group of reeds with selected natural frequencies, arranged to record the displacement at a series of known frequencies. From such a record, one can determine the frequency at which the greatest shock energy was delivered, and can more or less determine the nature of the disturbing excitation--whether it is harmonic, or impulsive. A combination of these two types of disturbances is difficult to interpret, but the gauge does allow a quantitative treatment to a considerable extent.

The gauges cited in the foregoing were supplemented by less plentiful gauges which may be divided into two categories - (1) gauges measuring relative displacements between members, and (2) seismic gauges which are sensitive to either acceleration or displacement, depending upon the design. In as much as these gauges are miscellaneous and were not used in any great quantity, they will not be described here.

Most of the instrumentation was arranged to serve for both tests without change. Part of the installation was however, shifted from above the waterline of the vessels in Test A to below the waterline for Test B, and special installations were made on vessels which appeared in only one Test, such as those within the 1000 yd circle.

Recovery of the instrumentation was obviously a prerequisite. Having in mind that the target vessels might be left several days after each test without its being possible to effect any damage control measures against progressive flooding, the selection of target vessels was deliberately conservative. However, enough coverage to be indicative of what happened was provided in to 750 yds of the intended Zero Point. The nearest of the APA's and the DD's carrying the principal installations was about 1100 yd from the Zero Point intended.

TEST A

In as much as Bomb A detonated at an appreciable distance from the intended Zero Point, a considerable portion of the instrumentation pattern was unbalanced; with the result that over 50% of it was situated in a region where the loading was about 1/3 of that which had been expected. However, a fair statement may be made as follows: at 1000 yds from the explosion the shock properties measured were within the range of operating experience, except for very light superstructure. In the case of this light superstructure, the maximum acceleration recorded at about 1000 yd was 20 g; the maximum impulsive velocity was in the order of 7-10 ft/sec. These values are relatively low, as shock experience goes, but the duration of the excitation was relatively long. Under this duration these values represent a condition which produces significant damage to light superstructure.

The failure of the radio links which controlled the remote starting of recording equipment, together with the error in the run-up of the timing signals, made an analysis of about 70% of the time recording instrumentation fruitless.

TEST B

The operation of the equipment in Test B, including the remote control of apparatus, was practically faultless. The performance was much better than is usually expected in field work of this sort.

The acceleration at about 1050 yd was less than 200 g; this was the closest location for the heavy instrumented vessels. The lowest acceleration which the mass plug accelerometers would respond to was 200 g, and none of these accelerometers indicated any response. At this writing the putty gauge recalibration has not been completed.

The maximum impulsive velocity recorded on the nearest ship thus instrumented (about 750 yd) was 17 ft/sec. The peak impulsive velocities showed an orderly decrease with distance; in addition, those gauges on the side of the ship away from the explosion showed a velocity inward but less than the velocities on the near side by a factor of 2 to 3. In several cases, they showed increasing velocities at the keel as one goes toward the center of the ships from the ends, indicating a summation effect that is not clearly understood. The records show a clearly defined depth effect, the peak velocity being less at lesser submergence below the waterline; this is taken to be a result of surface cut-off, but the region is one where this simple acoustic approximation does not hold for the shock wave, and this so-called surface cut-off effect requires further study.

The velocity meter records indicate a response which is attributed to a disturbance in the water arising from the ground wave in the bottom of the Lagoon, and the frequency of this disturbance corresponds to the natural frequency of a column of water of height equal to the depth of the Lagoon. This disturbance precedes the arrival of the water borne shock wave. The records show disturbances following the arrival of the primary shockwave; at this writing the cause is not definitely distinguished as reflections or as a possible shock emanating from the behavior of the collapse of the crater in the water. The peak values of the impulsive velocities are relatively low in relation to values which have been associated with damage. A value of 17 ft/sec. is roughly at the threshold of structural response which involves a small permanent deflection, and is at the beginning of the zone of significant shock derangement. Brief examination of the target vessels indicates for the APA's that the GASCONADE (750 yd), on which the value of 17 ft/sec was recorded, suffered some shock derangement, and that the BRISCOE (1100 yd) and ships further away suffered no appreciable shock derangement. These observations, and the impulsive velocities recorded, are consistent with past experience.

The strains follow the general characterization of the velocity meter records; they indicate loadings that are within the elastic range for BRISCOE (1100 yd) and ships further away, except for isolated cases of local plating response which have a maximum about at the yield point.

For vessels at 750 yd and further away, the roll of the vessels was not noteworthy. The maximum roll recorded was 14° (BRISCOE, 1100 yd). No installations were recovered inside 700 yd. The GASCONADE (750 yd) was substantially end on, so that the roll would have been subdued - the maximum roll on this vessel was 9°. The pitch of GASCONADE reached a maximum of 7°. None of these values represent any severe loading on the vessels.

In summary, it may be pointed out that at 750 yd and further, damage such as the structural response measurements indicate is shock damage and not of the severity which involves structural deformation of consequence. It should be kept in mind that this fact is attributable to the surface effect; for such a large charge exploded relatively so near the surface, the pressures near the surface outside of about a 400 yd radius are quite markedly reduced below the pressures which would be expected on the basis of the acoustic approximation.

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ENCLOSURE F

"Report of the Co-ordinator of Oceanography"

by

Cdr. Roger Revelle

D-986/1

Secret

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INTRODUCTION

The work of the oceanographic section had three objectives: (1) to obtain information for planning purposes on currents and diffusion in Bikini Lagoon and surrounding ocean waters in order to estimate the rate of decrease of concentration and the movement of radioactive materials released into the sea water by the bombs; (2) to determine the effects of the explosions on the waters, the living organisms, and the geological characteristics of the atoll - this included measurements of the waves and seismic disturbances produced by the bombs, particularly those in Test B, as well as changes in bottom depth and sediments and destructive or other ecological effects on the flora and fauna; (3) as a natural corollary of the last problem, to carry out an integrated investigation of all possible aspects of the natural environment - in brief to gain as much purely scientific information as time and facilities permitted concerning this little known area. In order to carry out these objectives, the cooperation of Federal scientific agencies such as the Geological Survey, the Coast and Geodetic Survey, the Smithsonian Institute, and the Fish and Wildlife Service was enlisted, as well as that of several universities and research institutions, and of Navy laboratories. The work of the oceanographic section was thus to a high degree a "joint" operation. Biological, geological, and physical oceanographic studies were begun in early March and continued until the end of August.

DESCRIPTION OF THE NATURAL ENVIRONMENT

GEOLOGY

1. Morphology of the Atoll

The atolls of the Northern Marshalls rise from an irregular ocean floor having extreme depths of over 3200 fathoms and a mean depth of 2500 fathoms. Many submerged, comparatively flat topped sea-mounts with horizontal dimensions of the same magnitude as the atolls rise to depths of 800 to 500 fathoms. One of these extends as a long ridge northwest from Bikini for about 20 mi at depths of 700 to 800 fathoms.

Bikini Atoll, centered at 11° 35'N, 165° 22'E, is roughly oval in shape, 23 mi long on the east-west axis, 13 mi north and south. It consists of a peripheral reef normally one-half mile to one mile in width studded with low islands and encircling a broad and deep lagoon. In order to determine the nature of the outer slopes of the atoll, numerous fathometer sounding lines were made, both parallel and normal to the atoll rim from as close to the reef as possible out to depths of 2200 fathoms. Near the reef the slope is very steep - almost perpendicular on the southwest side down to depths of over 30 fathoms. A fifteen fathom terrace fringes parts of the east and northeast sides of the atoll. The average slope between the surface and 300 fathoms is about 70%. The slope gradually decreases with depth and is about 25% at 1000 fathoms. The smoothness of the outer slopes is interrupted by long ridges which lie seaward of the major projections and angles of the reef. Bottom samples show that the outer slopes are mantled with coral and Lithothamnian (a species of shallow water calcareous algae) down to 15 fathoms. Between 15 and 200 fathoms Halimeda (another calcareous alga which grows characteristically in deeper water than Lithothamnion) is dominant on the surface. Since this alg. does not grow on the reef it must have originated on the outer slope. Below 200 fathoms calcareous sand decreasing in size with depth is found.

The total area of the lagoon is 641 km^2 (192 mi^2). The lagoon floor extends downward in an irregular, frequently step-like fashion from the atoll rim to depths of 25 to 30 fathoms at distances of one to two miles from the reefs. A 12 fathom terrace exists off Bikini Island surrounding a large depression which extends down to 20 fathoms. The maximum depth of the lagoon is 35 fathoms. This depth is found 4 miles west-northwest of Enyu Island. Coral "patches" or "pinnacles" with horizontal dimensions of one hundred to several hundred feet rise above the general level. Their tops are roughly equi-dimensional and may be at any depth from a few fathoms above the bottom to within 2 fathoms of the sea surface. The sides of some of these coral pinnacles are nearly vertical while others consist mostly of dead and loose coral fragments forming a talus slope of about 45°. Detailed bottom surveys indicate that in the target area there are about 20 coral pinnacles per square mile.

Planimeter measurements of hydrographic charts show that about 40% of the lagoon has a depth of 25 to 30 fathoms. Depths of 30 to 33 fathoms occupy an additional 35% of the total area. Above 25 fathoms, bottom areas become progressively smaller with decreasing depth, except for the zone between 0 and 5 fathoms, which extends over 8% of the lagoon, and has twice the area of the 5-10 fathom zone. Isolated coral patches and pinnacles, neglected in the measurements, would slightly increase the area of the shallowest zone.

The total volume of the lagoon below lowest low water is estimated to be 28 km^3, or 2.8×10^{16} cm^3. Of this volume, about 72% lies below the

7 fathom sill in Enyu Channel. Only about 4% of the water lies below the 30 fathom bottom of Eniirikku Pass, the deepest sill.

One third of the circumference of the atoll is composed of low islands and their associated sand bars. In general the islands are 12 ft or less above high tide level, although a few sand dunes reach a maximum height of 17 ft. The islands constitute the only portion of the rim over which flow of water is completely prevented. Between the islands are long stretches of broad, flat, and shallow reefs which together make up about half the circumference of the atoll. They are nearly exposed at low tides and at high tides are covered by up to 5 ft of water. The reef is broken by 8 passes or channels, which constitute about 20% of the circumference of the atoll. all on the south and southwest side. The largest one, Enyu Channel, accounts for three fourths of the total width of the passes and two thirds of the cross-sectional area. Its sill is roughly 7 fathoms deep and is visible from the surface throughout its length. In the deeper southwestern passes the remains of the reef are visible at the edges, shelving steeply toward the centers of the channels, which cut deeply into the reef. Where the deepest channel crosses the reef its depth is about the same as the maximum depth of the lagoon, suggesting that these channels possibly originated as outlets of a lake left behind during a period of glacially lowered sea level. The following table summarizes the dimensions of different portions of the atoll rim:

	Length	Area of cross-section below mean tide level
Islands	33 km	---
Reefs	47	.05 km^2
Passes	20	.30
Total	100	.35

2. Sediments of the Lagoon Floor

The coral patches are bare of sediments and covered with living or dead coral colonies and calcareous algae. Elsewhere the lagoon is floored with calcareous sediments. Near the rim of the atoll these consist of calcareous sand with many coral fragments and ripple marks or burrows, made perhaps by fish. Over most of the central region the sediments are made up of coarse, flaky fragments of Halimeda and other calcareous algae with minor admixtures of calcareous sand and mud. The organic matter content of these sediments is extremely low, about 0.5%. The only recent marine sediments with comparably small organic matter content are the red clays of the central ocean deeps far from land. The low organic matter content of the lagoon sediments must be due both to the slow rate of deposition - estimated to be less than 1.5 mm. per year - and the very low organic productivity of the atoll, which like the surrounding ocean is almost a marine desert.

3. Reefs

Calcareous algae belonging to the genus Lithothamnion are the dominant reef builders on the seaward edge of the reef, particularly on the windward side of the atoll, and corals are most abundant on the reef flat just inside this margin, particularly on the leeward side of the atoll. Although the number of coral species is large, more than 115 species having been identified to date, and the reefs are apparently in a healthy growing condition, the prolific coral growth which characterizes the reefs of Samoa, Fiji, Tonga and the Dutch East Indies is lacking.

Twenty-four detailed traverses, widely spaced around the atoll, were measured by geologists of the U.S. Geological Survey across the reefs from the seaward margin to the shores of islands or to the edge of the lagoon. These traverses, together with aerial photograhs, show that the reefs may be divided into more or less distinct longitudinal zones with the character of the zonation being somewhat different on the windward and leeward sides of the atoll. A generalized section across the reefs on the windward (east) side of the atoll would show the following zones:

(a) The Submarine Margin extends outward from the edge of the reef at low tide, sloping gently to steeply seaward. In a few places the slope near the reef is broad and regular, dropping only 10 or 15 ft in the first 100 ft from the reef edge; further seaward the slope increases to 45° or more so that the profile of the submarine margin is convex. In most places, however, the slope is irregular, but it always becomes steeeper near the outer edge. The submarine margin is formed largely of living algae with about 25% of the surface area being covered by growing coral colonies.

(b) The outer peripheral zone of the exposed reef consists of the Lithothamnion Ridge, 50 to more than 100 ft in width, rising 2 ft or more above low tide level, and composed mainly of pink to dark red living masses of the calcareous alga, Lithothamnion. Corals cover less than 5 to 10% of the surface area. This ridge is usually irregular with massive buttress like forms 25 to 50 ft wide extending normal to the reef, separated by surge channels 5 to 10 ft wide and 5 to 20 ft deep, which extend back 100 ft or more from the reef edge. These surge channels form a remarkably effective breakwater which absorbs nearly all the energy of the heavy trade wind swell that breaks almost continually on the reef. The remaining wave energy is utilized in building up a head of water on the reef which results in a continuous current flow from the ocean into the Lagoon. In places the growth of Lithothamnion shelves over the surge channels to form an algal platform underlain by connecting caverns.

(c) Immediately behind the Lithothamnion ridge there is usually a Coral-Algal Zone in which vigorously growing corals (both small branching forms and large encrusting types) cover 20 to more than 50% of the surface, the remainder being covered with pink algae. This zone, when present, is 25 to several hundred feet wide and is covered with one to six inches of water at extreme low tide.

(d) The Reef-Flat forms the major part of the reef. It consists typically of eroded coral and algal limestone covered with a thin veneer of sand, together with living foraminifera and soft brownish algae, with a few colonies of living coral. The reef flat is generally covered by six inches to one foot of water at extreme low tide. Extensive areas near shore are uncovered, while large tide pools are depressed below the general level and covered with one to more than four feet of water. Biological activity in these tide pools results in extreme variations of carbon dioxide content and pH, suggesting that the reef flat is an equilibrium surface the level of which is determined by the balance between physico-chemical processes of solution and redeposition of calcium carbonate. Where islands are not present, the reef flat may drop off abruptly to the sand and debris covered lagoon bottom, or it may shelve off gradually into the lagoon across a zone of scattered coral heads.

(e) Where islands are present, the reef flat may terminate against a zone of Beach Rock, consisting usually of consolidated gravel or boulders lying one to three feet above low tide level, but frequently being composed of a bedded beach sand that has been cemented into rock. Where the beach rock zone is absent, the reef flat extends to the edge of the sand beach of the island.

Around the leeward southwest and west sides of Bikini Atoll there are significant differences in the reef zonation as shown in the following generalized sections:

(a) The Submarine Margin is generally more regular and steeper on the leeward than on the windward side. One measured profile showed a dip of 45°or more to a depth of about 80 ft, followed by a vertical drop to a depth of at least 180 ft.

(b) No well developed Lithothamnion Ridge is present; the outer edge of the reef rises to a low crest, then drops a few inches to the coral algal zone beyond. Corals form 25 to more than 50% of the outer reef zone, the remainder being pink or orange colored Lithothamnion, and the edge of the reef is quite regular, with surge channels being absent or insignificant.

(c) The Coral-Algal Zone is almost invariably present and is usually extensively developed; in some places a great variety of corals cover the entire surface.

(d) The Reef Flat is comparatively rough and irregular, covered by one to four feet of water even at extreme low tide. Where islands are absent the reef flat may slope gently into the lagoon until it is four to eight feet or more below low water, the bottom covered with sand. Elsewhere, coral heads increase in size and numbers near the lagoon edge so that along some sections of the leeward reef and actual reef from, awash at low tide, is developed facing the wide lagoon.

(e) Where islands are present, the reef flat may end abruptly at a belt of Beach Rock or against a Boulder Rampart of loose coral head boulders.

4. Islands

There are 25 islands in the atoll, ranging in size from Yoran, 1000 ft long by 500 ft wide, to Bikini, two and a half miles long by one half mile wide. The larger islands occur at major bends in the reef, chiefly on the windward northern and eastern sides. Islands on the leeward western and southwestern sides of the atoll are smaller and more widely spaced.

The interiors of the islands are composed of unconsolidated calcareous sands and gravels, from pebbles to boulder size. Larger islands are dominantly sand, particularly on the north side of the atoll, while some of the smaller islands are formed almost entirely of boulders piled six feet or more above high tide level, presumably by storm waves. Around the island shores and in the intertidal zone consolidated deposits of boulders and sand are present as beach conglomerate and beach sandstone, but much of the shore line consists of sandy, pebbly, or boulder beaches.

The pebbles, cobbles, and boulders on the islands range in shape from angular, freshly broken fragments to well rounded, smoothly worn forms, and consist usually of fragments of coral colonies or of algal limestone. No non-calcareous rock of any kind was found. The sand is composed of beach type foraminifera together with fragments of coral, algae, mollusks and other skeletal material. Its average grain size usually exceeds one millimeter, although in wind blown dunes it is smaller. The beach sandstone and beach conglomerate are the result of very recent lithification of the beach sands and boulder beds and are usually similar in composition, bedding, and dip to the unconsolidated deposits with which they are associated. The conglomerate is generally well consolidated, while the sandstone, though often case-hardened on the surface is commonly very friable beneath the surface.

5. Subsurface Structure

Atolls are among the most uncommunicative of all geologic forms.

Geologic studies of the surfaces of atoll reefs and islands afford only meager evidence as to the origin, structure or internal constitution of atolls, and direct evidence bearing on these questions has been almost wholly lacking.

The central problem of atoll formation is essentially this: reef corals and calcareous algae can only grow within a few hundred feet of the sea surface, yet most atolls, like Bikini rise as isolated structures many thousands of feet above the ocean floor. Is the coral and other calcareous skeletal material simply a thin veneer over the surface of a flat platform consisting of rocks of other origin, or has there been a large relative rise in sea level which allowed the reef building organisms to slowly grow upward on a pile of their own skeletal remains? The resolution of these questions has formed one of the major problems of geology for the past hundred years.

In order to obtain direct information on the general nature of the subsurface structure and constitution of Bikini Atoll, a seismic refraction survey was carried out jointly by the Naval Ordnance Laboratory Low Frequency Group and the Seismology Group of the Oceanographic Section. Standard seismic techniques normally employed in geophysical oil prospecting were adapted for underwater operations and for use with equipment available at Bikini for water wave and low frequency measurements. Naval depth charges were used as explosives and were fired at intervals of a few thousand feet along profiles at the bottom of Bikini Lagoon. Detecting instruments were at fixed positions, generally at the ends of the profiles. Four refraction profiles were shot during the survey; the longest, from Enyu to Namu, being about 19 mi in extent. A total of 126 depth charges were fired. The positions of the profiles, the depth charges, and the receiving hydrophones are shown in Figure 1.

For each profile, the time intervals between the firing of each depth charge and the receipt of the ground wave signal at the receiving hydrophone were plotted against distance between the explosion point and the hydrophone. Such a plot for the Cherry-Enyu profile is shown in Figure 2. The points fall along three distinct lines, corresponding to three subsurface zones having discrete seismic wave velocities. The slope of any one line gives the velocity in the corresponding zone, and the depth to the top of the zone may be computed from the intercept of the line on the time axis. Variations in this depth along the profiles are estimated from the divergence between individual shot points and the average line. The estimated positions of the tops of the second and third zones along the Enyu - Cherry and Enyu-Namu profiles are shown in Figure 3.

Combining the results from all four profiles, the following conclusions are reached: Directly below the lagoon bottom there is a zone approximately 2000 ft thick which exhibits a seismic velocity (for P-waves) of 7000 ft/sec. Below this there is a zone of thickness varying from 3500 to 11,000 ft with a seismic speed of 11,000 ft/sec, except near the south edge of the atoll where the speed may be 9000 ft/sec. The third zone to which the seismic waves penetrated exhibits a speed of 17,000 ft/sec and is probably continuous at least to a depth of 20,000 to 25,000 ft. The top of this zone is irregular and may represent a surface of subaerial erosion or the top of an old submarine volcano. The highest point is beneath the southwestern part of the lagoon rather than near its center.

Although definite identification is not possible from the seismic data alone, it is most likely that the uppermost zone is composed of cal-

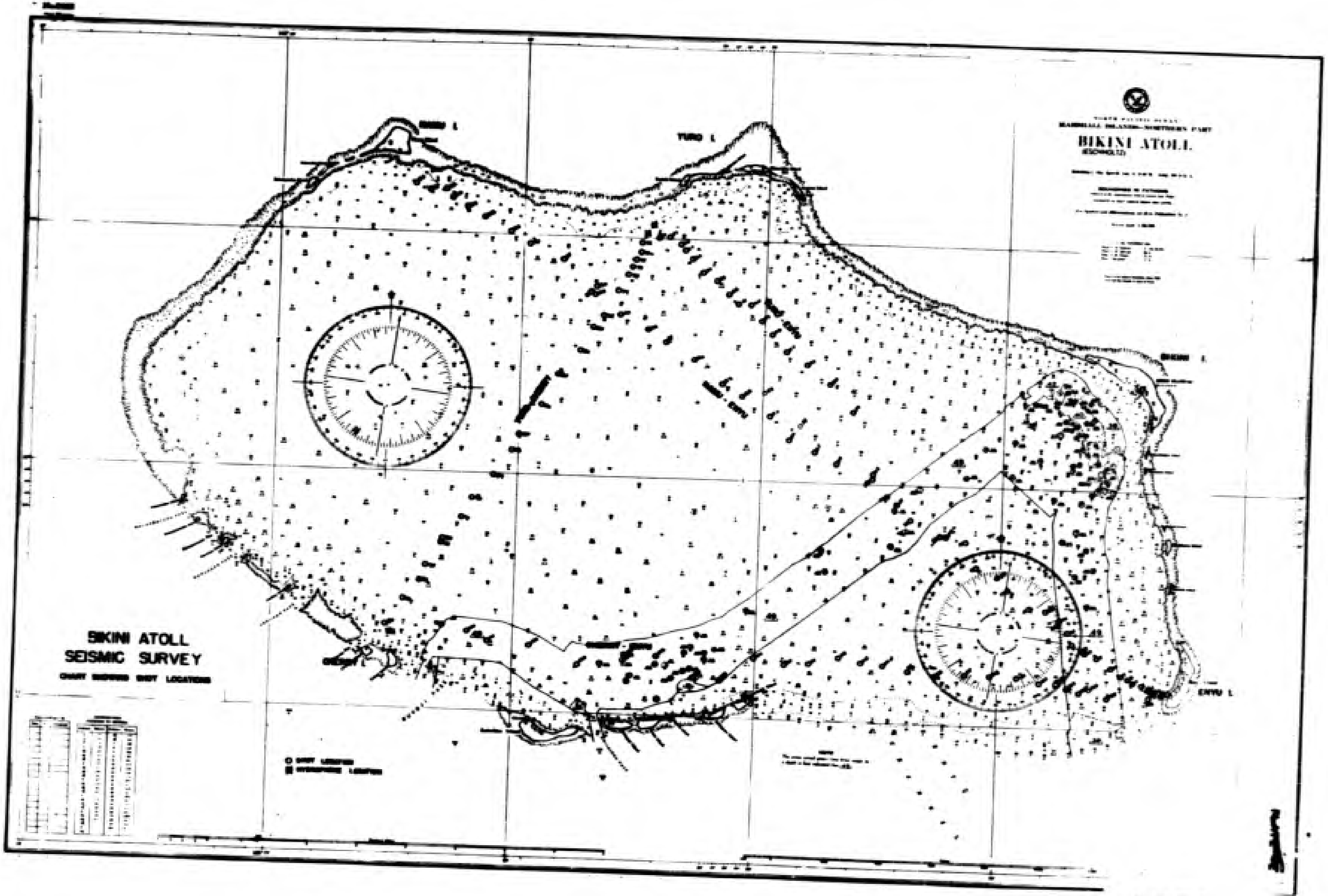

NORTH PACIFIC OCEAN
MARSHALL ISLANDS—NORTHERN PART
BIKINI ATOLL
(ESCHHOLTZ)
YURO I.
BIKINI I.
ENYU I.
BIKINI ATOLL
SEISMIC SURVEY
CHART SHOWING SHOT LOCATIONS
SHOT LOCATION
HYDROPHONE LOCATION

FIGURE 1

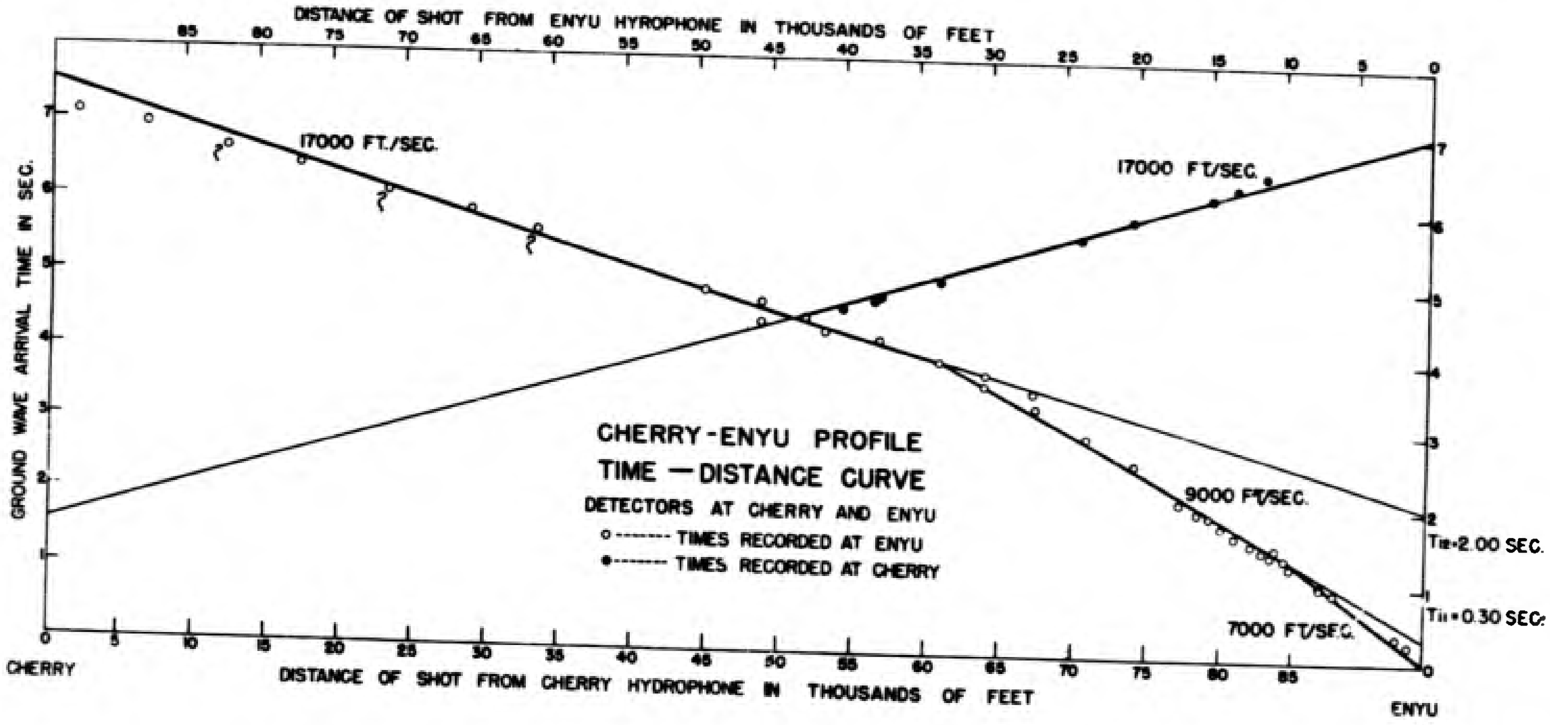
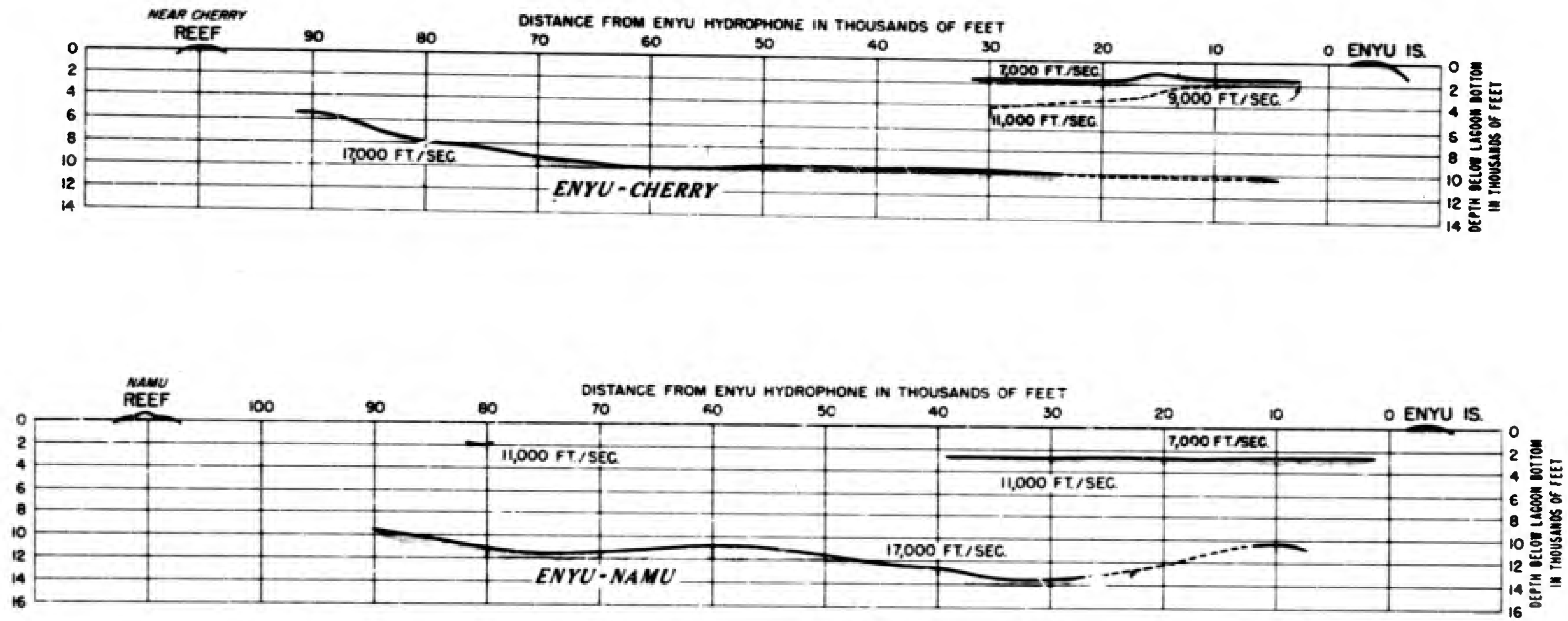

DISTANCE OF SHOT FROM ENYU HYROPHONE IN THOUSANDS OF FEET
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
GROUND WAVE ARRIVAL TIME IN SEC.
7
6
5
4
3
2
1
17000 FT./SEC.
17000 FT/SEC.
9000 FT/SEC.
7000 FT/SEC.
T_{III}=2.00 SEC.
T_{II}=0.30 SEC.
CHERRY-ENYU PROFILE
TIME — DISTANCE CURVE
DETECTORS AT CHERRY AND ENYU
○------- TIMES RECORDED AT ENYU
●------- TIMES RECORDED AT CHERRY
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
CHERRY
DISTANCE OF SHOT FROM CHERRY HYDROPHONE IN THOUSANDS OF FEET
ENYU

FIGURE 2



CROSS SECTIONS

SHOWING SUBSURFACE STRUCTURE INDICATED BY SEISMIC
SURVEY ALONG ENYU-CHERRY AND ENYU-NAMU PROFILES

FIGURE 3

careous sediments similar to those now being deposited on the floor of the lagoon. The deepest zone is probably the igneous basement, the observed speed comparing well with measurements in known basalt formations. The intermediate zone is the most difficult to identify. It could be pyroclastic material, pelagic limestone, or possibly shallow water calcareous limestone of a different type from that near the surface.

The geophysical evidence appears to support the view that considerable relative subsidence has occurred during the formation of at least some coral atolls. Only the core drill can give a definite answer, although valuable additional data could be obtained from other types of geophysical measurements such as magnetic and gravity surveys.

OCEANOGRAPHY

1. Open Ocean Area:

During the period March to August 1946 extensive surveys of the current regime and related oceanographic conditions were made in the area between latitudes 8° 30' to 14° N and longitudes 163° to 171° 31' E, with a few excursions beyond these limits south to 3° S and north to 20° N. Current movements down to 1800 meters were determined by the standard deep water oceanographic technique of measuring the vertical distribution of temperature and salinity at a series of stations, calculating the vertical and horizontal density distribution, and applying Bjerknes' circulation theorem. Use of this technique was necessary because the great depths of water around Bikini made it impractical to anchor in order to measure currents directly with current meters or current poles. In addition, temperature measurements down to 300 meters, using the bathythermograph, were repeated at intervals in a closely spaced network out to distances of about 50 mi from Bikini. Density distribution and currents in the upper 300 meters were computed from these measurements, after first calculating the salinity distribution from the temperature salinity correlation obtained at the oceanographic stations.

The Northern Marshalls Area lies in the path of the Northern Equatorial Current and the general circulation therefore from east to west. The current is strongest at the north and south boundaries of the area and along the north and south shores of atolls. Velocities near the surface in these localities are .7 to 1.0 knot. The currents are largely confined to the upper 300 meters, with little motion below 500 meters. In the lee of atolls, velocities are reduced and in at least two regions current directions are reversed, that is, the flow is from west to east. One of these regions is northwest of Bikini where a large elongated eddy (major diameter about 60 mi) rotates in a counter clockwise direction. A similar eddy lies in the lee of Ailinginae and Rongelap atolls. This eddy is large enough so that the current directly east of Bikini flows southerly, and southeast of Bikini it has an easterly component.

The vertical temperature structure in the vicinity of Bikini Atoll has a definite pattern consisting of a virtually isothermal layer from the surface to about 75 meters, an upper weak negative gradient (temperature decreasing with depth) from 75 to 150 meters, a strong main negative gradient or thermocline from 150 to 300 meters and a deep weak negative gradient decreasing in intensity from 300 meters to the bottom. The temperature decreases from 27 - 29°C at the surface, to about 3°C at 1500 meters. Temperature-depth measurements repeated at intervals of a few minutes for periods up to 48 hr showed the presence of internal waves or oscillations of the thermocline, with amplitudes up to 50 meters and a principal frequency corresponding to that of the semi-diurnal tidal period. These internal waves exhibit a 2 to 4 hr phase lag with respect to the tidal rise and fall at the surface.

A consistent temperature-salinity correlation exists between latitudes 8° and 14°N. Salinity was found to be rather uniformly 34.4 to 34.6% from the surface down to 60 - 70 M. Between 75 and 150 M the salinity increases to 35,1%° and then decreases to a minimum of 34.2 to 34.5%o at around 300 meters, below which depth it gradually increases to about 34.6%o near the bottom. Thus the salinity layers correspond to the temperature layers.

Although the horizontal variation of salinity near the surface was small, it was sufficiently definite and regular to allow the construction of relatively smooth isohalines, or lines of equal salinity. During the summer months these shift north and south as much as 50 miles over a period of two weeks.

Virtually no change in density occurs in the first 75 meters; a marked increase occurs between 75 and 300 meters. Below 300 meters the density gradually increases to the bottom.

2. Currents in Bikini Lagoon

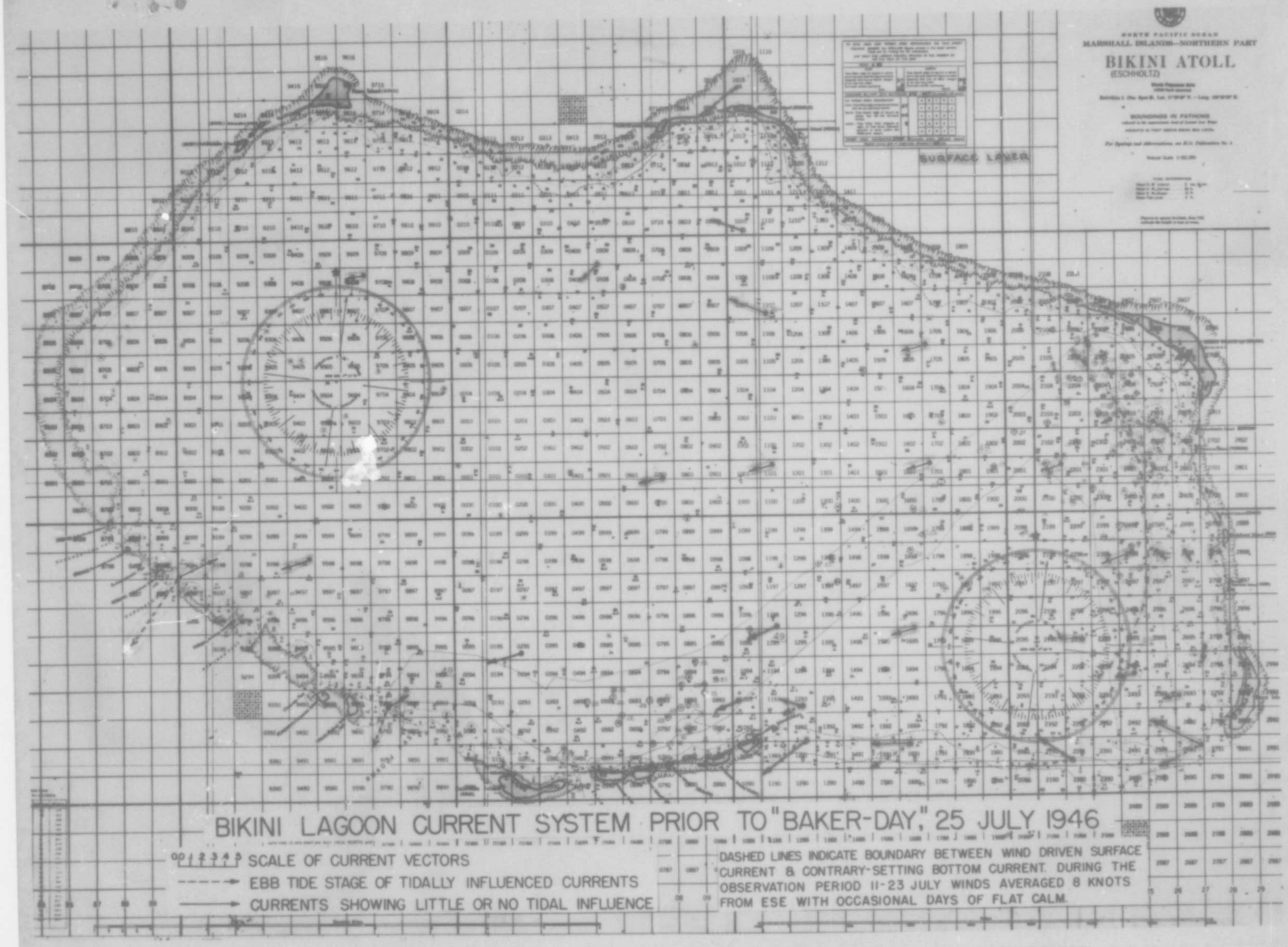
Currents and diffusion within Bikini Lagoon, and water exchange between the lagoon and the open sea were investigated in March and April during the period of prevailing east-northeast trade winds, and in July during the summer doldrum conditions. Data were thus obtained on the extremes of variability of the regime of water motion in the lagoon. The methods of observation included: (a) current meter measurements of velocity and direction from surface to bottom at fixed stations in the lagoon and the southwestern passes over a tidal period; (b) the use of current poles to determine the average drift of the upper 15 ft of water over periods of 8 hours to a day and a half; (c) the release of dye markers on the reefs and at fixed points in the lagoon to follow current motion and horizontal diffusion over periods of several hours; (d) the use of a small model adjusted for dynamic similarity at points where field observations had previously been made. The combined data from these various methods give a more complete picture of the water circulation in and around Bikini Atoll than is available for any other American harbor.

In March and April, during the period of steady east-northeast trade winds averaging 15-18 knots, the current system in the lagoon consists primarily of a wind driven surface current toward west-southwest down to about 40 ft, overlying a slower bottom current toward east-northeast which extends from about 40 ft to the bottom. The speed of the surface current varies from .3 to .6 knots depending on wind speed, and its depth also increases somewhat with higher winds. The velocity of the bottom current is roughly one-third of the surface current velocity. These two currents form a continuous rotary circulation with bottom water upwelling at the eastern end of the lagoon and surface water sinking over the western portion. The rate of upwelling is of the order of 12 to 24 ft per hour, and occurs within two to three thousand yards of the eastern lagoon margin from Bikini to Enyu Islands. The sinking is broadly distributed over the western quarter of the lagoon at a rate of 3 to 8 ft per hour. Over the eastern and northern reefs oceanic water flows in continuously at velocities of .4 to 1 knot. This inflow results principally from the piling up of water on the reefs by the long oceanic swell generated by the trade winds. The difference in water level between the reefs and the lagoon is about 1.5 ft. Continuous outflow varying from .3 to .6 knots on flood and ebb tides respectively occurs in the western part of Enyu channel, but the volume of water involved is small and orginates largely as oceanic inflow in the southeastern corner of the atoll. In the southwestern passes and on the western reef, the current reverses with the tide. The maximum tidal flow through the passes averages 1.5 knots during flood and 2.5 knots during ebb. Over the western reef the currents are weak, ranging in speed from .1 to .3 knots.

Although an average of about 3.8% of the water in the lagoon flows out through the southeastern passes on each ebb tide, this tidal interchange is relatively ineffective in flushing the lagoon. An estimated 40% of the water flowing out through the passes comes from the central and eastern parts of the lagoon; the remainder is oceanic water which entered the passes on the preceding flood. Only about 10% of the water entering the passes on the flood tide becomes thoroughly mixed with lagoon water and carried into the general lagoon circulation. By far the major portion of the water in the central and northeastern parts of the lagoon has come in over the northern and eastern reefs. As water flows in at a rate of about 3% of the lagoon volume per day, it is absorbed into the rotary circulation of the lagoon, thus contributing to the gradual renewal of the lagoon water while at the same time the latter is being flushed out of the southwestern passes at a rate of 3.2% of the total lagoon volume per day. (The excess of true lagoon water being flushed out in comparison to the reef inflow originates in the flood tide inflow through the southwestern passes). At this rate of flushing, half the water in the lagoon is replaced by new oceanic water in 22 days, and nine-tenths is replaced in 2.5 months.

When the current survey was repeated in July the winds were mainly east-southeast averaging 10 knots but there were occasional southerly winds of 5 knots and some days of calm. Under the influence of these lighter more variable winds the surface current still sets down wind but much more slowly (less than .3 knots) and the bottom current (less than .1 knot) opposes it insofar as the geometry of the bottom of the lagoon permits. Because of this geometry the bottom current tends to align itself with the major east-west axis of the lagoon. Thus even in times of southerly wind when the surface current is setting northwest or north-northwest with sufficient vigor to flow out to sea over the northern reefs the bottom current is turned only east-southeast. For this reason the zone of upwelling along the eastern reef is a permanent feature under all winds having an easterly component. The upwelling deep water splits into two currents opposite Bikini Island which flow in opposite directions parallel to the reef before rejoining the general surface flow toward the west. When the wind has a westerly component the current system tends to reverse itself, the surface current responding quickly while the bottom current changes direction only after a day or more.

During the summer months the heavy northeasterly swell so characteristic of the winter and spring months is absent and little or no water comes in over the northern and eastern reefs. In contrast to the spring condition, the net flow through Enyu channel is inward and this is the principal source of ocean water for replenishment of the lagoon. The net flow through the southwestern passes is still outward but is 50% less than in the winter and spring. When the wind is light and southerly and the surface ocean water has a salinity and density less than that in the lagoon, a thin surface layer of relatively light ocean water may be driven in through Enyu channel and out over the northern reefs with little or no mixing with the deeper water of the lagoon. Such a condition existed after the bomb explosion on B Day. Occasionally during the summer months the salinity and density of the water outside the lagoon are such that a rapid replenishment of nearly all the water in the lagoon by ocean water flowing in through Enyu Channel takes place in a period



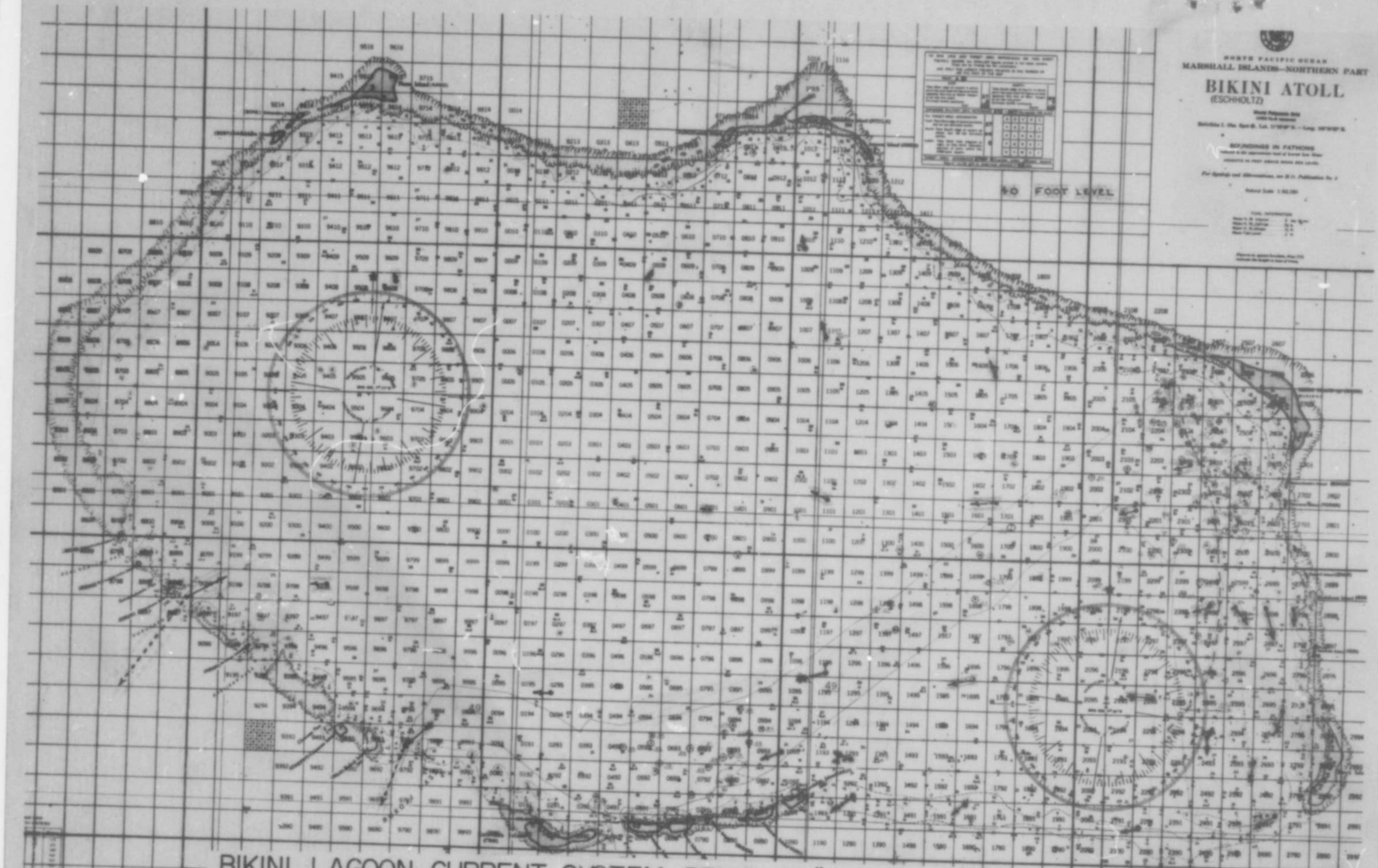
BIKINI LAGOON CURRENT SYSTEM PRIOR TO "BAKER-DAY," 25 JULY 1946

0 1 2 3 4 5 SCALE OF CURRENT VECTORS

EBB TIDE STAGE OF TIDALLY INFLUENCED CURRENTS

CURRENTS SHOWING LITTLE OR NO TIDAL INFLUENCE

DASHED LINES INDICATE BOUNDARY BETWEEN WIND DRIVEN SURFACE CURRENT & CONTRARY-SETTING BOTTOM CURRENT. DURING THE OBSERVATION PERIOD 11-23 JULY WINDS AVERAGED 8 KNOTS FROM ESE WITH OCCASIONAL DAYS OF FLAT CALM.



BIKINI LAGOON CURRENT SYSTEM PRIOR TO "BAKER-DAY," 25 JULY 1946

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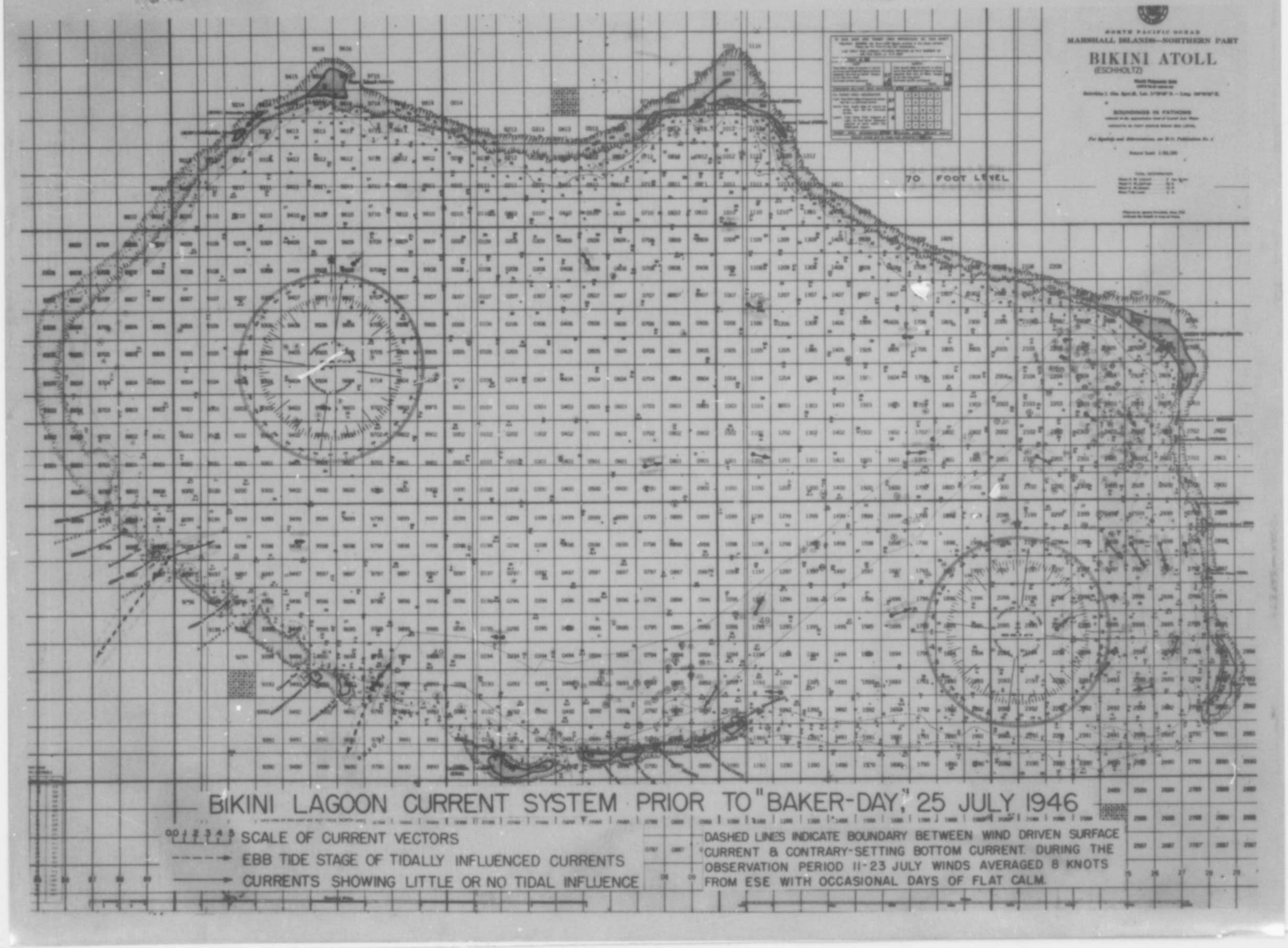

BIKINI LAGOON CURRENT SYSTEM PRIOR TO "BAKER-DAY," 25 JULY 1946

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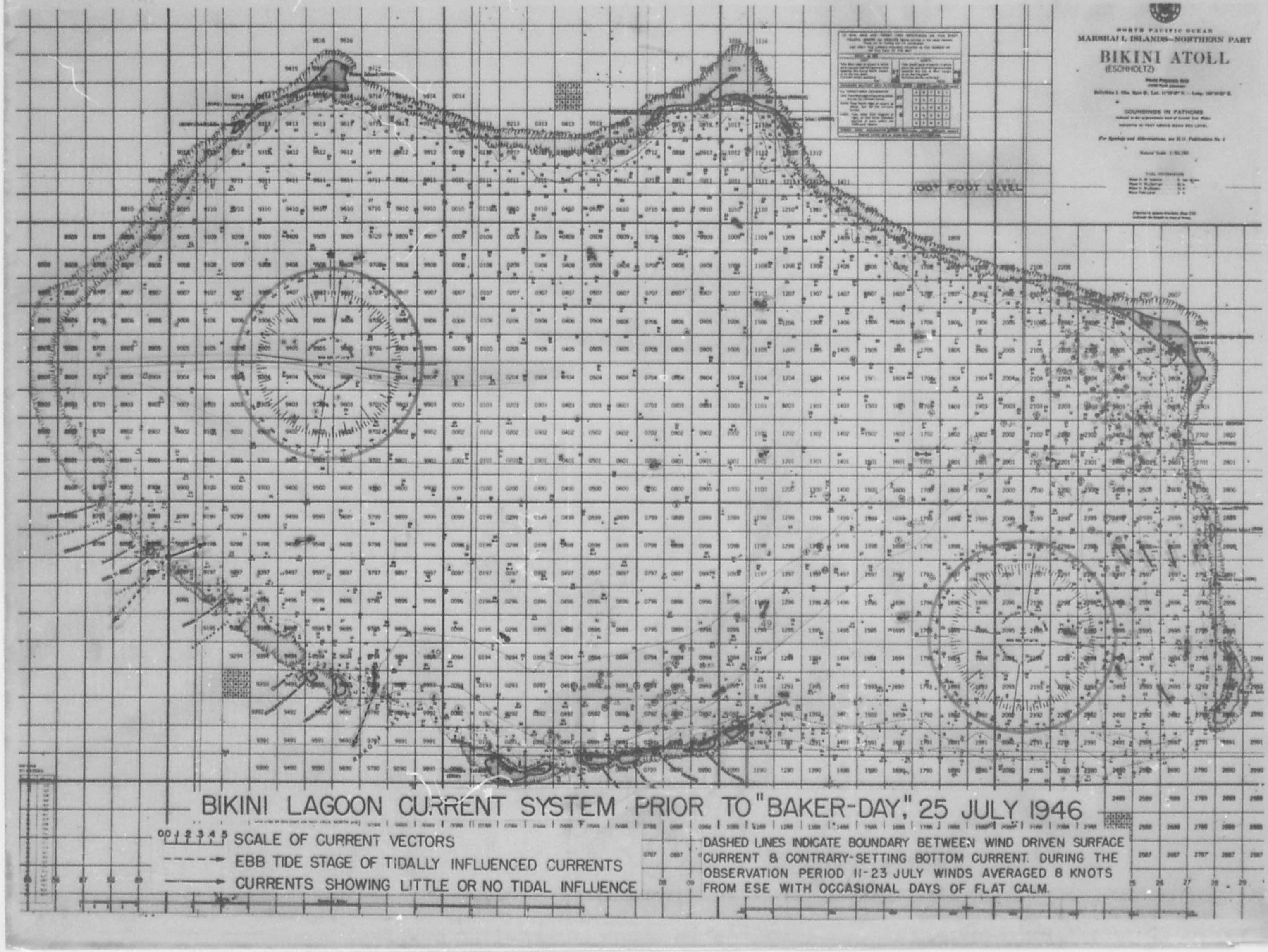

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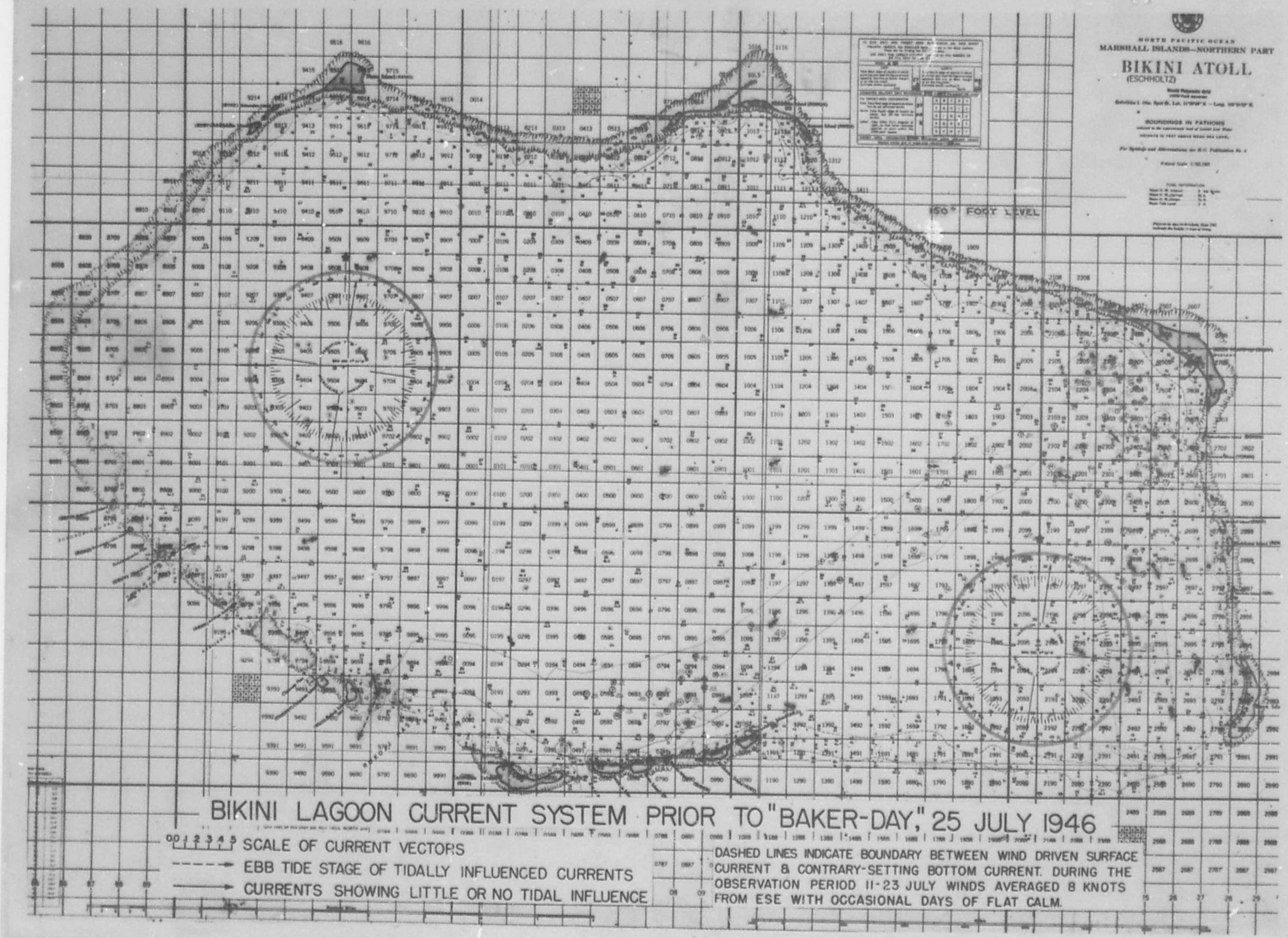

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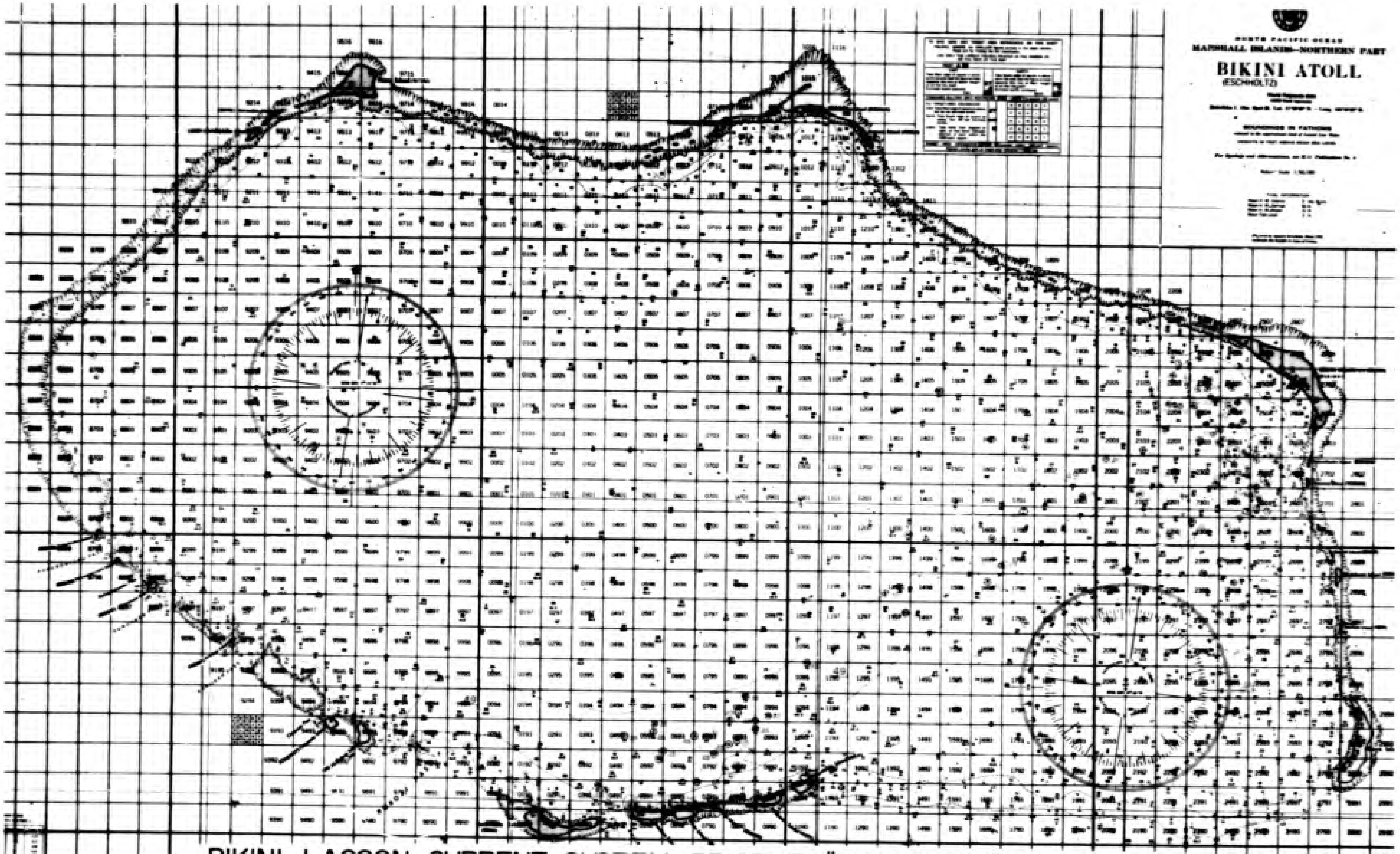

BIKINI LAGOON CURRENT SYSTEM PRIOR TO "BAKER-DAY," 25 JULY 1946

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of a few days. Although this condition is abnormal it apparently occurred between Baker plus 5 and Baker plus 8.

The current system in the lagoon under the influence of prevailing weak east-southeast winds of July is illustrated in Figure 4. This figure consists of a series of transparent overlays superimposed on a chart of the atoll. Each transparency represents a layer of water in the lagoon and the water motion within it. Figure 5 is a photograph of the water motion observed in the model of the atoll with a simulated wind from the east-southeast. Just before the photograph was taken a drop of dye was placed at a position corresponding to the target center. The surface current carried part of the dye northwest and west parallel to the reef while the remainder moved with deeper water east and southeast.

The current system shown in Figure 4 was modified on B Day by the presence of a light breeze from south-southeast with a velocity probably less than 5 knots. Light variable breezes alternating with periods of calm persisted on B Day plus 1 day after which the winds increased somewhat and hauled to the southeast. The wind driven surface current probably slackened to less than .1 knot but was apparently reinforced during the first 36 hours after the explosion by a head of relatively light surface water at Enyu channel which caused a shallow surface layer to flow in through Enyu channel and out across the reef between Bikini and Amen Islands. The bottom current flowed at a low velocity eastward from the target area and south along the reef. On Baker plus 2 and subsequent days the surface currents in the general target area resumed their normal course toward the northwest at velocities of .1 to .2 knot and the bottom current continues to flow in the opposite direction at velocities of a few hundredths of a knot towards the zone of upwelling along the eastern reef.

3. Vertical and Horizontal Diffusion in the Lagoon

The process of diffusion on the laboratory scale is well understood. Because of the random motion of molecules, dissolved material initially present in a small volume will spread from the region of high concentration to regions of low concentration. The rate of change of concentration in any small volume is proportional to the rate of change of the gradient of concentration, that is, $\frac{\partial C}{\partial t} = \eta \frac{\partial^2 C}{\partial x^2}$

The proportionality factor η is known as the coefficient of molecular diffusion. It is a small number, 2×10^{-5} for salt, and is the same in all directions. In the ocean, vastly more efficient turbulent processes take part in the mechanism of diffusion but a similar equation may be used for the rate of change of concentration in any element of volume. The coefficient of proportionality is designated as A (austausch coefficient) and is usually much more than a million times as large as the molecular coefficient. The coefficient A depends upon wind speed, currents, density gradients, and the general scale of the phenomena and is different for horizontal and vertical directions. Since the intensity of turbulence may vary in the direction of the gradient, the basic differential equation for turbulent diffusion is: $\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(A \frac{\partial C}{\partial x}\right)$ (1)

Previous measurements have shown the value of A_v, the coefficient of vertical diffusion, to vary from 1 to 320, and the value of A_h the coefficient of horizontal diffusion, to vary from 2×10^6 to 4×10^8.

Turbulent diffusion, in combination with the two-layer current

FIGURE 5 - MODEL OF BIKINI SHOWING WATER MOVEMENT WITH SOUTHEAST WIND, A FEW SECONDS BEFORE THE PHOTOGRAPH WAS TAKEN, A DROP OF DYE WAS PLACED AT THE TARGET CENTER; THE SURFACE CURRENT CARRIED SOME DYE TO THE NORTHWEST; THE REMAINDER WAS CARRIED SOUTHEAST ALONG THE REEF.

system and radioactive decay were the principal factors bringing about the reduction of the maximum concentration of radioactive materials in the water of Bikini Lagoon. Diffusion was also responsible for the continual increase in the size of the contaminated volume. In the absence of turbulent diffusion the initially contaminated water mass would have moved down current without increase in size and with a radioactive concentration decreasing only in proportion to the rate of radioactive decay. Very little is known about the nature of diffusion in the ocean so that it was not possible to estimate in advance what the numerical values of the horizontal and vertical turbulent diffusion coefficients pertaining to Bikini Lagoon should be. Several experimental methods were therefore employed for determining these values.

The uniformity of the water in Bikini Lagoon from top to bottom, particularly in the spring months, gives qualitative testimony to the effectiveness of vertical diffusion. To obtain quantitative measurements the following three methods were used: (1) the relationship between wind velocity and surface current was used to compute values of the coefficient of eddy viscosity which in uniform water should equal the value of A_v; (2) the vertical temperature distribution was measured throughout a diurnal cycle and A_v was computed from the decreasing amplitude and increasing phase lag of temperature variations with distance below the surface; (3) the coefficient was computed from measurements of the rate of mixing of water coming over the reefs (which could be identified by its somewhat higher temperature, salinity and oxygen content) with the water in the lagoon. The results from all three methods agreed well together and fitted excellently the theoretical expression for the eddy viscosity of homogeneous water under the action of a wind of velocity U;

$$A_v = 4.3 \times 10^{-4} U^2 \qquad (2)$$

According to this expression A_v for a 15 knot wind, typical of Bikini during the spring months, is 240 cm^2/sec, while for the 5 knot winds existing on Baker and subsequent days, A_v was probably about 27 cm^2/sec.

Additional analysis and study of the data obtained at Bikini will be necessary before a complete elucidation of the diffusion of radioactive materials produced by the explosions is possible, but the following discussion illustrates the application of diffusion theory and observational results to these problems.

Let it be assumed that at time $t = t_0$, the contamination is initially distributed uniformly throughout a surface layer of thickness Z_1 and that the initial concentration in this layer is C_1. For depths Z greater than C_1, $C = 0$ when $t = 0$. The solution of equation (1) for these boundary conditions is:

$$\frac{C}{C_1} = \frac{1}{2}\left\{ H\left(\frac{Z \quad Z_1}{\sqrt{4A_v t}}\right) - H\left(\frac{Z - Z_1}{\sqrt{4A_v t}}\right)\right\} \qquad (3)$$

where $H(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-\alpha^2} d\alpha$ is the probability integral, which is tabulated.

in Pierce and other tables of integral. At the surface $C = C_0$ and (3) reduces to:

$$\frac{C_0}{C_1} = H\left(\frac{Z_1}{\sqrt{4A_v t}}\right)$$

The following table gives the ratio of concentration at different times to initial surface concentration for water at the surface and at 15 meters below the surface (the depth of current reversal at Bikini) together with the rate at which the contaminating material goes into the layer below

15 meters (expressed as percent per hour) when A_v = 250 cm^2/sec and Z_1 = 250 cm. These conditions are approximately those which prevail after an air burst during the spring months at Bikini. Similar conditions would have existed over an area of about 25 km^2 if Test B had been conducted during March or April at Bikini.

Time minutes	$\frac{C_o}{C_1}$	$\frac{C_{15}}{C_1}$	ercent initial material going into lower layer per hour
0	1.00	0	0%
12	.32	.01	22%
30	.22	.06	35%
60	.15	.08	35%
120	.11	.075	24%
240	.075	.06	15%

The table shows that in four hours the concentration in the upper 15 meters has become virtually uniform and that 60% of the contaminated material has diffused below 15 meters. The decrease in the percentage rate at which the material diffuses below 15 meters after one hour is related to the fact that the lower layer is being filled with contaminated water, and the vertical gradient is thereby being reduced. Actually, under the conditions prevailing at Bikini, the leading edge of the surface layer is continually flowing over uncontaminated water and the percentage rate of diffusion into the bottom current at the leading edge of the contaminated surface layer would increase to more than 35% per hour after one hour. The conditions shown in the table would apply to the trailing edge of the surface layer.

In an underwater atomic explosion such as that in Test B, the entire radioactive contamination outside a zone a few hundred meters in radius around the target center is initially on the surface, having fallen out as rain from the base surge and the cauliflower cloud. Several minutes are required before this surface contamination diffuses downward sufficiently to approximate the conditions necessary for application of equation (3). Near the surface, the scale of turbulence is reduced by the presence of the boundary and A_v is approximately given by the expression:

$$A_v = Z -- 0.6 \qquad (4)$$

Equation (4) only applies above a depth Z_1 at which A_v given by equation (4) is equal to A_v computed from equation (2). Below this depth the coefficient is assumed constant down to a short distance above the bottom.

Letting S equal the total contamination per unit surface area, the concentration at any depth Z and time t is given by:

$$C = \frac{S}{t} e^{-\frac{Z}{t}} \qquad (5)$$

Equation (5) only applies during the first few minutes after the contaminated rain has fallen on the surface. When half the contaminating material has diffused below the depth $Z = \frac{1}{2} Z_1$, equation (3) may be used as a fairly adequate approximation of reality.

In a system of two superimposed currents flowing in opposite directions such as that in Bikini Lagoon, vertical diffusion can play a very important part in spreading the contaminated material and in decreasing the maximum concentration. As an example, let it be assumed that the contamination is initially uniform throughout a cylinder extending from the surface to the bottom. The material initially present in the upper layer is diffused downward into that part of the previously uncontaminated lower layer over which the surface current is passing. Likewise, the previously uncontaminated upper layer overlying the path of the contaminated deep water receives material by diffusion. Let the thickness of the upper current layer be h and the current speed V. The thickness of the lower layer is h' and the current speed is V'. In order to satisfy the requirements of continuity in a virtually closed body of water

$$V'h' = Vh \qquad (6)$$

Take a small element of volume of width dx extending from top to bottom of the lagoon. Along one side of this volume element the average concentration in the upper layer is C and in the lower layer is C'; along the other side the concentration in the upper layer is $C + \frac{\partial C}{\partial x} dx$ and in the lower layer it is $C' + \frac{\partial C'}{\partial x} dx$. In the upper layer the amount of radio active material entering, minus the amount leaving equals:

$$Vh\,C - Vh\left(C + \frac{\partial C}{\partial x} dx\right) = -Vh \frac{\partial C}{\partial x} dx$$

In the lower layer, the corresponding difference is:

$$V'h'\left(C + \frac{\partial C'}{\partial x} dx\right) - V'h'C = V'h' \frac{\partial C'}{\partial x} dx$$

Adding these two expressions and substituting for V'h' from (6) we obtain for the rate of change of the average concentration throughout the volume element:

$$\frac{\partial C}{\partial t} = Vh\left(\frac{\partial C'}{\partial x} - \frac{\partial C}{\partial x}\right) dx$$

The rate of change of concentration at a given location in the lagoon is thus proportional to the difference in the horizontal gradients of concentration between the upper layer and the lower layer.

Though the area of contamination is increased by current transport and vertical diffusion when the latter is not too rapid, the area of maximum concentration moves more slowly than the currents and tends to remain near the target center. Much of the material being carried away by the upper current diffuses downward into the bottom current and flows back to the target area. Likewise, the material in the bottom current leaving the center diffuses upward and returns in the surface current. Indeed, if the rate of vertical diffusion were sufficiently rapid to maintain a uniform concentration from top to bottom along any vertical line, the maximum concentration of contaminated material would remain at the target center and horizontal diffusion would be the only process causing an increase in the contaminated area. Under these conditions $C = C'$ and

$$\frac{\partial C'}{\partial x} = \frac{\partial C}{\partial x} \quad \text{therefore:}$$

$$\frac{\partial C}{\partial t} = Vh \left(\frac{\partial C'}{\partial x} - \frac{\partial C}{\partial x} \right) dx = 0$$

The concentration under the action of currents and very rapid vertical diffusion thus remains constant in each element of volume.

After Test B, horizontal diffusion played an important role in decreasing the maximum concentration of radioactive material and in increasing the volume and area of contamination. The coefficient of horizontal diffusion, A_h, appears to depend on the radius R, of the area of contamination, and on the wind velocity. At Bikini, the ration A_h/R was measured prior to Test B by observing horizontal diffusion of patches of dye released in the water. After the test, the spread of.radioactive material released by the bomb was measured from B Day to B Day plus 8 days by repeated observations of the concentration of radioactive material at a network of stations throughout the lagoon. Both methods gave a volume for A_h/R of about .5.

The differential equation of horizontal diffusion in polar coordinates is:

$$\frac{\partial C}{\partial t} = \frac{A_h}{R}\left(R\frac{\partial C}{\partial R^2} + \frac{2\partial C}{\partial R}\right) \qquad (7)$$

If $A_h = .5$ and if, when $t = 0$, $C = C_1$ inside a circle of radius R_1 and equals zero outside this circle, two of the solutions of (7) are:

At the center, $\frac{C}{C_1} = 1 - e^{\frac{-R_1}{.5t}}\left(1 + \frac{R_1}{.5t}\right)$

For $R \geq 2R_1$; $\frac{C}{C_1} \quad \frac{1}{2}\,\frac{{R_1}^2}{.25t^2}\,e^{\frac{-R}{.5t}}$

Immediately after Test B the maximum concentration was high in the inner 1000 yards and decreased out to an average distance of 3000 yards beyond which there was no appreciable contamination. The average value of R_1 can therefore be taken as approximately 2×10^5 cm. Computed ratios of concentration at different times to the initial concentration resulting from horizontal diffusion alone, both for water at the center and at 4 and 8 kilometers away from the center are given in the following table:

Time after explosion In Days	$\frac{C}{C_1}$ At Center	$\frac{C}{C_1}$ 4 km. From Center	$\frac{C}{C_1}$ 4 km. From Center	Observed Maximum Concentration
1	.94	.0008	0	100 +
2	.67	.03	.0004	109
3	[illegible]	.06	.003	51
4	.34	.07	.01	23
5	.25	.07	.01	15
8	.11	.05	.02	1

The last column of the table gives maximum observed values of radioactivity in the lagoon for the first 8 days after B Day corrected for decay and expressed in arbitrary units. Over the first 5 days the observed maximum concentration decreased somewhat more rapidly than the computed maximum. It is thus evident that vertical diffusion in combination with the two layer current system played an appreciable part in reducing the contamination near the center and in spreading the contaminated material over the lagoon. (The fact that the maximum concentration on B Day plus 2 days was higher than on B Day plus 1 day is due to the extreme "patchiness" of the distribution of radioactive material compared to the spacing of sampling points). The observed maximum concentration on B Day plus 8 days is only about one-tenth of the computed maximum. The apparent total quantity of radioactive material in the lagoon was also much less on B Day plus 8 than during the first 5 days. It is therefore probable that between B Day plus 5 and B Day plus 8 the density of the water just outside Enyu Channel was such as to cause a rapid replenishment of most of the lagoon water by ocean water coming in through the channel and a consequent removal of most of the radioactive material. A different method of analysis was employed for the samples collected on B Day plus 8 than on previous days and it is possible that the apparently very low concentrations observed are due to inacurate calibration.

The observed linear increase in A_h with increasing radius of the contaminated area means that the radius increases uniformly with time in rough accordance with the expression:

$$R = R_1 \quad Kt$$

At Bikini the value of K was about 1.5 cm/sec and the average concentration at any time over the entire contaminated area is therefore approximately given by the expression:

$$C_t = \frac{C_1}{1 + \frac{3t}{R_1} + \frac{2.25\,t^2}{R_1^{\,2}}}$$

The following table gives the calculated radius of the contaminated area and the corresponding ratio of the average concentration to the initial concentration for the first 8 days after B Day assuming that R_1 was 2×10^5 cm. Comparison of this table with the preceding one indicates that R calculated in this manner is the radius where the concentration is somewhat less than one hundredth of the initial value.

Time after Explosion Days	$\frac{C}{C_1}$ Average over contaminated Area	R Kilometers
1	.37	3.3
2	.19	4.6
3	.115	5.9
4	.077	7.2
5	.055	8.5
8	.026	12.4

BIOLOGY

1. Organic Productivity

One of the major factors in evaluating the possible effects of the bombs on the organisms and reefs of the atoll was the overall level of organic activity, that is, the rate of production of organic matter by plants, from carbon dioxide, water, dissolved phosphate and other nutrient salts. In addition, this problem is of great scientific interest. Coral atolls are the largest organic structures on the earth's surface and their existence and rate of growth in the barren central parts of the ocean are among the most intriguing questions of geology and marine biology.

The organic production in the lagoon and on the reefs was determined from measurements of diurnal and local changes in the biologically active substances, dissolved oxygen and phosphate. The average total production of oxygen in the lagoon itself was found to be .007 milliliters per liter of water per 24 hours about the same as that in the subsurface ocean waters surrounding the atoll. No appreciable seasonal variation was observed. Each milliliter of oxygen produced corresponds to .54 milligrams of carbon converted into organic matter by photosynthesis. There are thus .19 grams of organic carbon produced in the water column under each square meter per day or 70 grams per square meter per year, an annual total of about 5000 tons per year for the entire lagoon. The production per square meter is lower than that found in any other shallow water ocean areas which have been investigated except the English Channel.

Measurements of the change in oxygen content of water passing over the reefs show an organic carbon production of 3.5 grams per square meter per day or roughly 1 kilogram per year, many times that in the lagoon or the outside ocean. The reef is thus a self supporting entity. Making the reasonable assumption that the amount of precipitation of calcium carbonate is no more than two to four times the amount of organic carbon, the maximum possible rate of growth of the reef is computed as one to two milligrams per year or three to six feet per thousand years. This rate is much less than that measured in productive areas of the East Indies. By an entirely separate calculation the maximum rate of sedimentation on the lagoon floor, based on the amount of calcium carbonate available for utilization by the Halimeda living on the bottom, was found to be about 1.5 millimeters per year.

From the above computations it is evident that the quantity of living organisms in the waters of the lagoon should be relatively very small compared to the reef population, and that the latter itself is sparse when compared to the reefs in other areas. This presumption was born out by biological sampling of the lagoon and reef fauna.

2. Bacteria

Marine Bacteria form an essential link in the cycle of life in the sea, because they are the only organisms capable of transforming organically bound phosphate, nitrate, and other nutrient substances into inorganic dissolved salts which can be utilized by a new generation of plants. An average of a few hundred bacteria per milliliter was found in the lagoon waters near the surface, while in the lower layers only about thirty per milliliter were found. Although the numbers near the surface are about the same as those in moderately fertile inshore waters of temperate latitudes, the mean for the water column from surface to bottom is very much smaller.

Even more striking is the absence of bacteria in the sediments of the lagoon floor, less than 100 to 200 per gram as compared with hundreds of thousands to millions in sediments off the California coast. This low concentration corresponds to the low organic matter content of the sediments.

3. Marine Plants

The small, one-celled plants which make up the phyto plankton population of the sea are very scarce at Bikini, but sessile marine algae are of major importance. Calcareous forms such as Lithothamnion make up the principal building material of the reef and Halimeda, another calcareous alga characterized by its segmented platy structure, grows in abundance on the lagoon floor and the outer slopes of the reef. Noncalcareous algae form a close, inconspicuous felt on the reef flat; they are the basic food of many of the reef fishes.

4. Marine Animals

The small marine invertebrates which comprise the zooplankton population are sparse, though more abundant than the phytoplankton. Evidently the zooplankton graze on the floating plants right up to the limit of photosynthetic productivity. A considerably larger population exists in the lagoon than in the waters outside, and the characteristic lagoon species are different from the open ocean forms.

The different reef zones described in the chapter on the geology of the atoll, together with the topography and sediments of the lagoon floor, afford a variety of environments for bottom living invertebrates and fishes. Each environment has a characteristic faunal assemblage. Because of their bulk and abundance corals and their relatives are the most striking invertebrates, but many non-sessile forms also occur, including numerous mollusks, echinoderms and crustacea. Among these, the black sea cucumbers of the reef flats, the various species of hermit crabs, several different types of giant clams (Tridacna and Hippopus) and cowries, conches, and other highly ornamented gastropods are especially noticeable.

The reef and shallow water fishes of Bikini are moderately abundant and highly varied. They are often brilliantly colored. The population was considerably greater on the western reef than on the upwind side of the atoll. Over forty thousand individual specimens, belonging to well over a hundred species, were collected and shipped to the National Museum for study. Many of these fishes are algal feeders and were thus particularly susceptible to radioactive contamination after Test B.

A systematic program of fishing for pelagic and semi-pelagic fishes belonging to the tuna family and other families of commercially valuable forms was carried out over the six months period from March through August. These fishes were found to relatively scarce throughout the area but were most abundant in and outside the southwestern passes.

5. Land Plants

The land vegetation of Bikini is relatively simple. About 50 species are represented, of which some 20 are common to all the larger islands;

[redacted]

half a dozen of these are nearly invariably present on any permanent land. The most important shrub is *Scaevola*/another is *Suriana*; both of these types are found right behind the beach. *Tournefortia* *Guettarda* occurs here also but forms small trees in the wooded areas as well. These are parasitized by *Cassytha*, a yellow, leafless vine. Introduced on the larger islands are coconuts and *Pandanus*, and perhaps *Tacca*, to the natives the only important food plants. Wood for the construction of their light houses is furnished by *Tournefortia* and for tools by the hard *Pemphia*, but this latter is now rare. The largest tree, approaching 100 feet, is *Pisonia*, but its wood is too soft for economic use. The dominant climax vegetation of the larger islands is sometimes Pisonia, sometimes the orange-flowered *Dordia*, and occasionally a mixed growth. Few fleshy fungi, a few lichens, one moss, no liverworts, and no ferns were found in these islands.

C. Land Animals

Land animals are not numerous in species on Bikini Atoll. One species of land Isopod crustacean is found under rotting logs, in the moister parts of the forest floor. Two of the largest species of Hermit Crabs are land species, and their giant relative, the Coconut Crab is to be found on most of the larger islands. One species of true Land Crab is also present. At Bikini, as elsewhere, there are probably more species of insects than of any other animal group. Moths, six species of ants, perhaps as many kinds of beetles, a true bug, a few kinds of cockroaches, one small katydid, one dragon fly, and a few types of bees are all common. Musca sorbens, a species of fly, is present in great numbers and is a very annoying pest. Bird mosquitoes are present in the rainy summer season, but are not found as adults at other times. Centipedes, a small species of Scorpion, and a few types of spiders are found. One of the latter is very common. There are four species of small land snails which because of their size are inconspicuous, (the largest being less than one-fourth inch long) although very numerous.

Apparantly there are only three species of lizards native to Bikini, no snakes whatever, and no turtles except the sea turtle. Mammals are represented by only one species, a small native field rat.

The birds of Bikini may be divided into three groups according to their habitat, the sea birds, the shore birds, and a single species of migratory land bird, the New Zealand Cuckoo. The sea birds, all fish eaters, include five resident species of tern (Crested, Common Noddy, White Capped Noddy, Black Naped, and together with the migrant Sooty Tern, the Redfooted and Fairy), Brown Boobies, and Frigate Birds. The shore birds are with one exception migratory; they include the Ruddy Turnstone, Golden Plover, Bristle-thighed Curlew, four species of Sandpipers, and the resident Reef Heron.

EFFECTS OF THE BOMB EXPLOSIONS

PREPARATIONS FOR WAVE MEASUREMENT

As originally developed, the task of measuring surface water waves produced by the bomb tests appeared to have three aspects: (1) Measurements of possibly very high wave generated directly by the explosions in and around the moderately deep water of the target area; (2) investigations of the transformation of these waves in shallow water and the nature of their action on beaches and shore installations, particularly on Bikini Island itself; (3) measurements of any secondary waves resulting from effects of the explosion, for example it was thought possible that the seismic vibrations caused by the explosive impulse might trigger large slides of sediment down the outer slope of the atoll and set up a small scale seismic sea wave or "tsunami".

Two types of observations were selected as primary in measuring the waves in the target area: (1) changes of pressure at the bottom, and (2) displacement of the free surface, both as a function of time. For the former it was necessary to modify existing wave measuring instruments to enable them to withstand high intensity shock effects of short duration, and yet to measure relatively slow pressure changes of less than half a pound per square inch. The instruments finally selected were (1) a modification of the BuOrd Acoustic system Mark 1 mod. 4 shore recording bottom mounted hydrophone equipment, with special hydrophones designed to withstand several thousand pounds pressure; and (2) self contained, clock operated, pressure recorders, called "turtles", shock mounted in a heavy steel case and containing a filter system designed to damp out high peak pressures of short duration. These were designed and tested to record slow changes in hydrostatic pressure of less than 0.25 psi in the presence of shock pressures from depth charges exceeding 4000 psi. The Test B results indicate, however, that although these instruments could withstand high peak pressures, they were damaged and made inoperative within 2000 ft of the target center, apparently by intense mass accelerations of relatively long duration.

The Mark 1 mod 4 hydrophone systems were constructed, planted and operated by the Naval Ordnance Laboratory Low frequency Group; five hydrophones were in operation for Test B and two for Test A, on a line between the target center and Enyu Island at distances of 4500 to 30,000 ft from the explosion. Thirty turtles were set out for Test B by groups of the Oceanographic Section on two lines, one between the target center and Bikini Island and one leading from the center toward Namu Island; horizontal distances from the target ranged from 600 to 63,000 ft. Sixteen turtles were employed in Test A.

Displacement of the free surface as a function of time in the target area was measured by echo sounders mounted on target ships and on buoys astern of the ships and by aerial and tower photography. Most of the echo sounders were of the portable type; the remainder were the shipboard models already installed on the target vessels. The principal modifications necessary for these equipments were fitting of more open-scale recorders, clock starting devices, and accurate timing mechanisms. Duplicate installations of echo sounders on shipboard and on buoys about 50 feet astern of the ships were made at several locations to determine the extent to which the rise and fall of the ships with time, (recorded by the echo sounder as a variation in bottom depth) would correspond to the displacement of the sea surface. Test with depth charges in February and March 1946 showed that satisfactory wave records could be obtained with echo sounders outside the zone of subsurface cavitation from the explosion.

Twenty eight echo sounder installations were made for both Tests A and B, at distances from 750 to 12,000 ft in Test A, and from 1700 to 12,000 ft in Test B. These installations were spread about equally on the various lines of ships radiating out from the center.

In laying out the wave photography, experience gained in studies of waves and surf off the United States coast was employed. In these studies a technique had been developed for taking simultaneous aerial and ground photographs of waves using radio links for synchronization and specially designed intervalometers for accurate timing. By taking simultaneous still photographs with long-focal-length aerial cameras from two ground positions and one aircraft, all approximately at right angles from the points of interest, accurate three dimensional plots of waves had been obtained. Analysis of the special situation at Bikini showed that wave height could best be determined in photographs from towers on the islands, while aerial photography was best suited for determining wave length and velocity and for mapping the positions of each crest at successive times. Plans were laid on this basis for tower heights and locations at Amen, Bikini, and Enyu Islands on lines intersecting approximately at right angles and for assignment of three PBM planes to the wave photographic program. Important wave phenomena were expected to last for many minutes; it was therefore desirable to employ slow-speed aircraft flying in a large circle centered at the target. The radio transmitter which triggered all the cameras simultaneously was installed in one of the PBM's.

In measuring characteristics of the waves as they approached the island shores and broke near the beaches, principal reliance was placed on photogrammetric analysis of the accurately timed still photographs from the towers. In this connection it was necessary to make detailed soundings of the shallow water areas in from of the towers in order to determine the depth of breaking and related effects of inter-action between the bottom and the waves. Sets of poles fitted with electrical or mechanical means of measuring the maximum rise of water level were installed in shallow water off Bikini. These "electric contactor beach poles" and "tin can height indicators" were also installed well inland in case waves occurred significantly higher than those predicted. Extensive photography of all the structures and conditions on Bikini Island was carried out to enable a study of wave damage to be made in case of an inundating wave. To guard against possible failure of the photography due to radioactive fogging or other causes and to furnish an immediate close-up estimate of events after the explosion, television installations were also made on Bikini. The operation of this equipment was quite satisfactory but the excellence and completeness of the aerial and tower photography made the television results of secondary significance.

Provision for measuring a possible seismic sea wave or a seiche (standing wave in an enclosed or partially enclosed basin such as Bikini Lagoon) was made by installation of BuOrd Acoustic System Mark 1 mod 1 hydrophones on Yuro and Namu Islands and on the coral shelf facing Bikini outside Eniwetok, Wotho, Rongelap, and Kwajalein

Atolls. Negative results were obtained at all these installations at other atolls, indicating that no seismic sea wave or similar disturbance of appreciable magnitude occurred.

Planning of design characteristics and locations of the wave measuring instruments was considerably handicapped during the early months of 1946 by lack of adequate data for prediction of the waves to be expected from the tests. Although extensive model studies and experiments on waves produced by explosions had been carried out by various groups, including the Los Alamos Laboratory, the New Zealand Seal Project, and the Explosive Research Section of the Bureau of Ordnance, no data were available for water as shallow in proportion to equivalent charge radius as that at Bikini. Accordingly an extensive series of model studies in which depths were scaled in proportion to the cube root and the fourth root of the ratio of charge weight to the expected equivalent tonnage of 20 kt were carried out. Among the major questions, both qualitative and quantitative in character, on which it was hoped these tests would throw light were the following:

1. Does the explosion generate the first wave directly or does this wave result from the collapse of the cavity produced by the explosion?
2. What height, shape and sequency of waves can be expected near the explosion point for a given weight of charge?
3. How do wave height, period, and length vary with radial distance in water of uniform depth?
4. What are the characteristics of the plume or column of water produced by the explosion? Is this column blown upward directly by the expanding gasses or does it result from the collapse of the

cavity blown into the water?

5. What is the maximum elevation reached by the column?
6. What is the maximum diameter near the base of the column and what is the rate at which the column diameter develops?

The results of the model studies proved very valuable in adjusting the sensitivities and locations of the wave instruments, in determining optium timing and camera characteristics for photography of wave and water motion, and in planning certain aspects of the Task Force operations which depend in part on reliable predictions of wave height and characteristics of the water column.

RESULTS OF TEST A WAVE MEASUREMENTS

Four bottom pressure observations (two turtles and two NOL hydrophones) of water motion due to the blast were obtained in Test A, at horizontal distances from the point of burst of 300 to 6500 ft; one echo sounder record at 3100 ft also gave positive results. In the remainder of the records, water waves from the blast were masked by wind waves.

Near the burst there was first a depression of the water surface, amounting to about 6 ft and lasting for about 8 sec, followed by a rapid rise to a height of 2 ft above mean level. The surface then slowly receded to the normal level, which was reached nearly 40 sec after the blast. At greater distances there was also a first slight depression of the surface lasting for about 10 sec, followed by a rise of smaller amplitude, again of about lo sec duration.

From a preliminary examination of the records, the total height from trough to crest appears to vary inversely with distance, being roughly represented by the relationship; $HR = 4300$, where both height, H and horizontal distance, R, are in feet.

The water motion from the air burst is of considerable theoretical interest, and it is hoped that later analysis of the rather meager data available may prove valuable in testing quantitative theories of this motion.

RESULTS OF TEST B WAVE MEASUREMENTS

1. The Records.

Usable records of bottom pressure due to surface water waves were obtained from 14 "turtles" at horizontal distances of 2100 to 25,000 ft from the target center, and from 5 of the hydrophones planted by the Naval Ordnance Laboratory Low Frequency Group at 4500 to 30,000 ft. In 4 of the turtle records outside of 12,000 ft, no measurement of the time interval from the blast to the arrival of the first wave is available. Sixteen echo sounder records of surface displacement due to wave motion were recovered at distances of 2520 to 11,680 ft. The first part of the surface wave motion at distances greater than 1100 ft can also be obtained from the tower photographs by measuring the vertical and horizontal displacement of buoys and target vessels. Near the center, ships were obscured by the base surge before the top of the first crest was reached, but at greater distances most of the high waves passed the ships before the arrival of the base surge. It is expected that a complete photogrammetric analysis will require several months and will result in more than doubling the number of points at which wave data are available, as well as extending the distance range. The combined data will represent one of the most complete series of wave observations in shallow water ever obtained and should form a satisfactory basis for extensive theoretical analysis.

All wave recording instruments placed within 2000 ft of the LSM 60 were badly damaged and none gave a readable record.

Examples of curves read from echo sounder and bottom-mounted wave pressure records are shown in Figure 6. In addition, measurements from photographs taken from the towers on Bikini and Enyu are given for the SARATOGA, the LST 133, LCT 874, and the LCT 1078. The curves are plotted in sequence with increasing distance from the explosion.

The excellent agreement between the photographic measurements and the echo sounder records on the two LCT's at distances of 7280 and 8800 feet should be noted in Figure 6. The reliability of the echo sounder records at some distance from the explosion is also indicated by the fact that very close agreement was found between pairs of records from the same ship, when o. echo sounder was mounted on shipboard and the other was suspended from a buoy about 50 ft astern of the vessel. On at least one ship near the explosion, however, the echo sounder is believed not to have recorded the maximum wave height. According to Dr. Penney the pipes placed by him on the deck of the LCT 816 were bent due to water motion; thus this craft must have been partly submerged by the wave, and the echo sounder could not follow the surface motion. The amount of bending of the pipes corresponded to a relative motion caused by a wave 36 ft high. Since the LCT itself was undoubtedly moving through the water, the actual water velocity probably corresponded to a wave of a height greater than 36 ft. The echo sounder record, on the other hand, showed a maximum height of only 30 ft.

The two curves based on bottom pressure records shown in figure 6 have been corrected to surface height by multiplication by a correction factor. For most of the records at Bikini, this correction, which depends on the depth of the instrument and the period of the wave, amounts to a 10 to 25% increase in the wave height from trough to crest above the recorded bottom pressure change. The amount of correction is uncertain to the extent that impulsively generated waves do not conform in shape to ordinary surface gravity waves, and also in the case of the innermost records, because of the relatively great wave heights. Considerable uncertainty exists also, as to the effective period of the first and normally highest wave.

Although only a preliminary photogrammetric analysis has been made, measurements of ship motion due to waves inside 2100 ft were carried out for the SARATOGA, the HUGHES, the YO-160 and the LST 133. In no case was it possible to measure more than the first rise of the ships due to wave motion. Thereafter the vessels were obscured by the outward moving base surge which engulfed the area. The results of these measurements are shown in Table I. From measurement of the ratio of crest height to trough depth on echo sounder and bottom pressure records it appears that the actual wave height from trough to crest at each ship was probably at least twice the values shown in the last column of Table I.

2. Qualitative Description of Waves Produced by the Bomb:

From figure 6, it will be noted that the first wave to arrive is always a positive crest, followed by a trough which on the average decends at least as far below the still water level as the crest rises above it. This trough is followed by a train of waves. Near the explosion point the first crest is apparently somewhat higher than the succeeding ones, both above the undisturbed water level and in total height above the succeeding trough. At greater distances from the explosion the highest wave is frequently one of those in the train which follows the first wave. The maximum height in this train passes backward to later and later waves as the distance from the center increases. In the Naval Ordnance Laboratory record from 22,620 ft for example the ninth wave is slighyly higher than the first one. In almost all cases the height of the second crest is smaller that either the heights of the adjacent crests or the depths of adjacent troughs.

The number of waves measurable by either the echo sounders or the

TABLE I
MINIMUM VALUES FOR HEIGHT AND ARRIVAL TIME OF FIRST WAVE CREST
(From Preliminary Photogrammetric Analysis)

Ship	Initial Distance From Explosion (feet)	Measured Horizontal Displacement of Ship (feet)	Minimum Distance of Ship From Explosion At Passage of First Wave Crest (feet)	Least Value For Wave Arrival Time (Seconds)	Measured Rise of Ship (feet)
SARATOGA (Stern)	1120	Not Measured	1120 +	12	43
SARATOGA (Bow)	1340	60	1400	12 +	29
YO-160 (Bow)	1635	145	1780	18	36
HUGHES (Stern)	1920	40	1960	22	Not Measured
LST 133 (Stern)	1900	Not Measured	1900 +	21	24
LST 133 (Bow)	2180	Not Measured	2180 +	24	25

bottom pressure recorders increased from 3 at 2100 ft from the center to 6 at 10,000 ft and 14 or more at 22,000 ft. Actually a very large number of waves was produced by the bomb explosion as is shown in Figure 7, an aerial photograph taken 5 min after MIKE hour in which over 20 waves can be seen. In this, as in other aerial photographs taken many minutes after the explosion, the entire area of the lagoon discernible through the clouds is covered with concentric waves radiating from the bomb center. Most of these were apparently too low for instrumental measurement.

The time interval between the first wave and the following ones increases from less than 20 sec at 2100 ft to 40 sec at about 12,000 ft. The intervals between succeeding crests are somewhat smaller for later waves than for the earlier ones, but the period of each individual wave noticeably increases with increasing distance.

Although duplicate measurements near the same point, as in the case of the CORTLAND, WAINWRIGHT, LCT 1078, and LCT 874 are quite consistent, considerable variability both in time of arrival of the waves, and in their height and other characteristics, is seen between different records at approximately the same distance. Two possible reasons may be suggested for this variability: (a) the waves were not symmetrical in all directions, for example, in general, instruments located NE of the bomb recorded somewhat higher waves than those to the NW. (b) the irregular bottom topography caused variations in wave height both because of loss of energy due to breaking over coral heads and because in shoaling water there is a decrease in wave length and consequent increase in wave height.

Some of the bottom pressure records on the line between Bikini and the target center show a disturbance at about 580 to 620 sec after Mike hour which is apparently caused by reflection of the first wave back from the beach toward the target area. In the Naval Ordnance Laboratory line toward Enyu this reflected wave appears at 700 to 850 sec.

3. Maximum Wave Height As A Function of Distance:

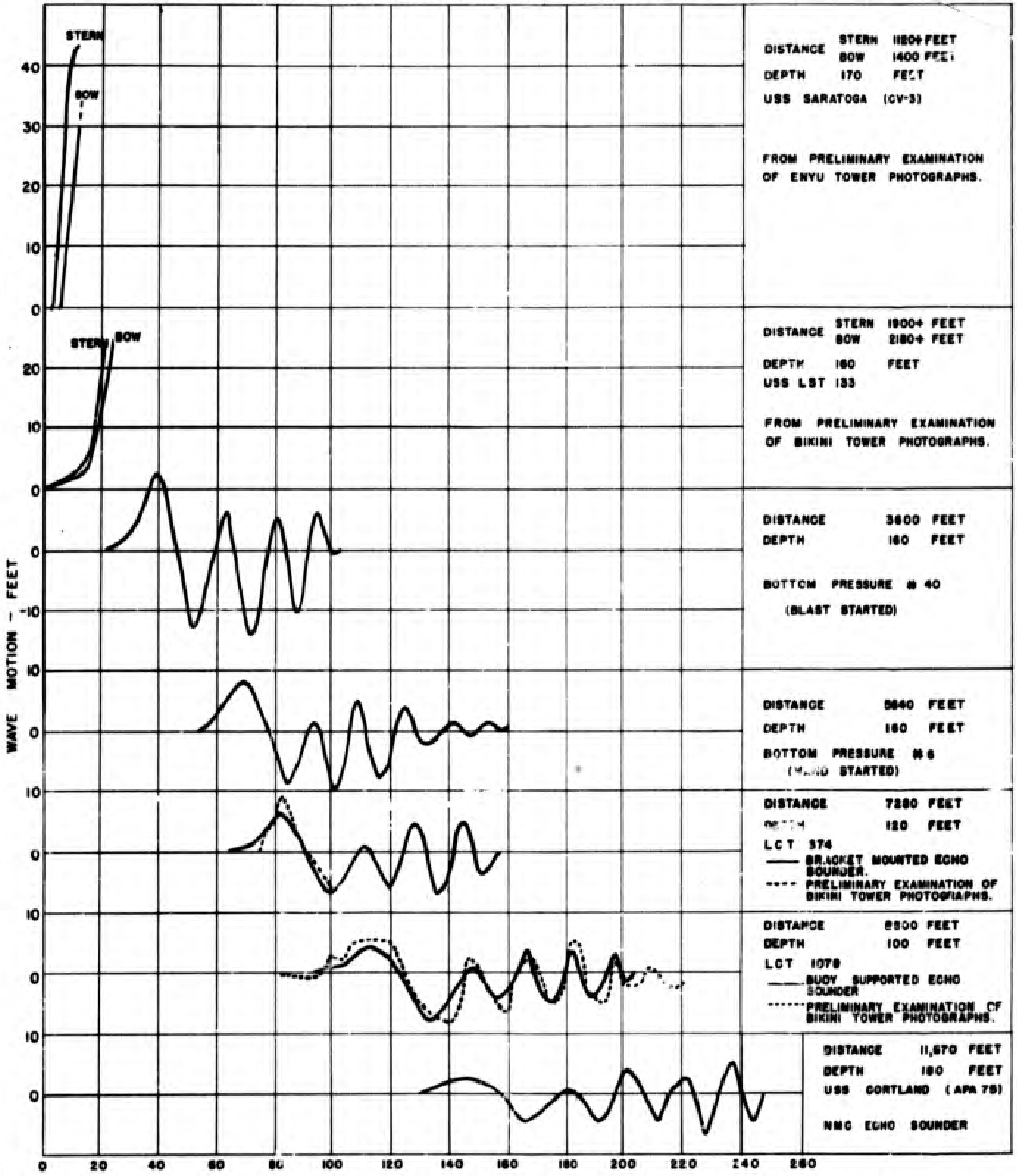
This and succeeding quantitative discussions in sections 3 through 9 are based primarily on the records obtained from "turtles" and echo sounders and on a relatively cursory examination of the tower photographs. The analysis given herein is preliminary and subject to change when other data from the photogrammetry and from the NOL hydrophones are more fully considered.

The maximum wave height for each of the turtle and echo sounder records was plotted against horizontal distance from the explosion in Figure 8. By maximum wave height is meant the greatest distance from any crest to the next preceding or following trough. A straight line was fitted by eye through these points and extended inward to a distance of a thousand feet from the target center. This line was found to conform to the equation:

$$HR^{.9} = 42700$$

After the line of best fit had been drawn, maximum wave heights from the Naval Ordnance Laboratory hydrophones were plotted on Figure 8. It may be seen that these points cluster moderately well around the line previously drawn.

TEST BAKER SURFACE WATER WAVES



TIME AFTER EXPLOSION — SECONDS

FIGURE 6

FIGURE 7 - AERIAL PHOTOGRAPH FIVE MINUTES AFTER EXPLOSION SHOWING WAVES RADIATING FROM TARGET CENTER.

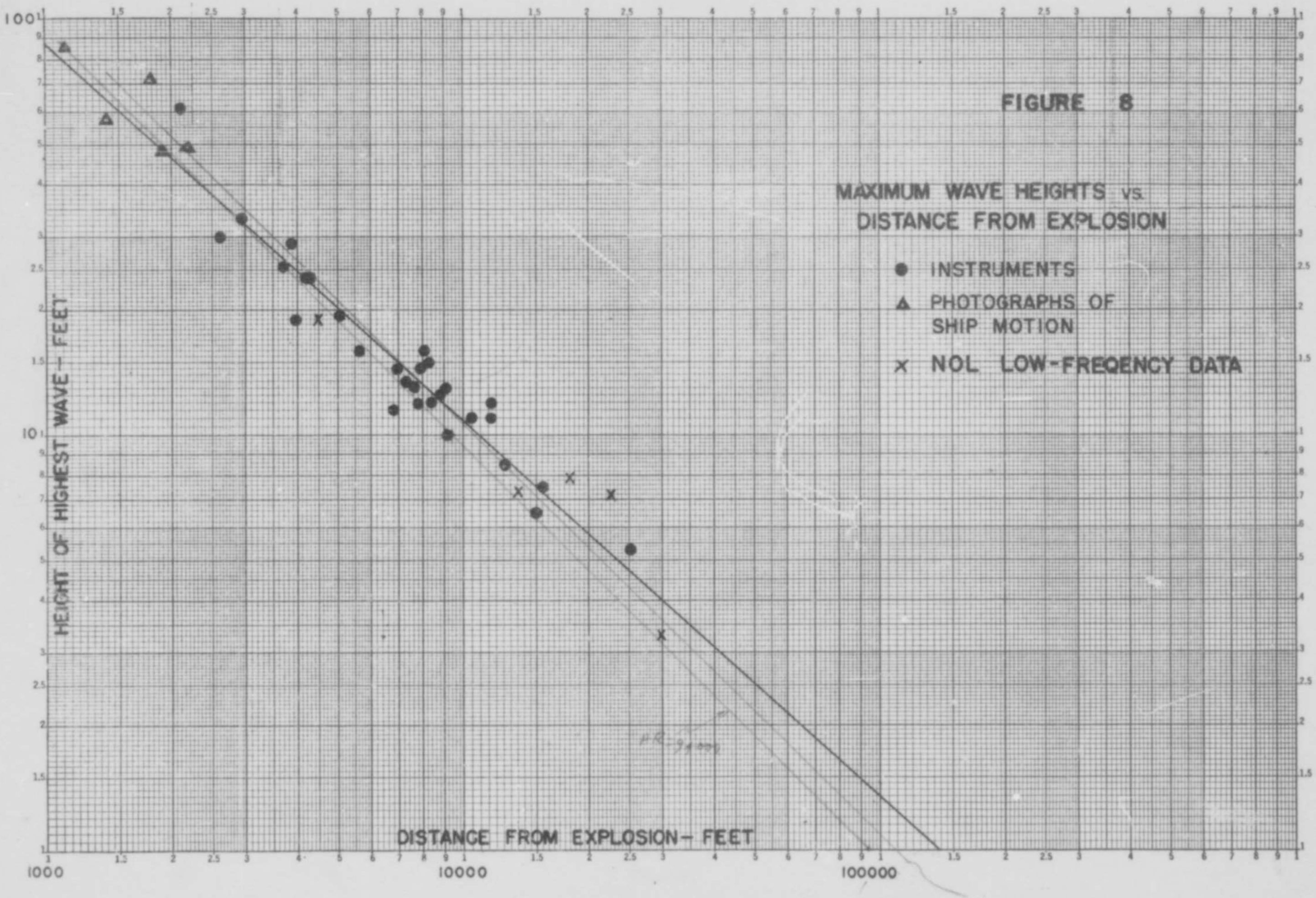


FIGURE 8

MAXIMUM WAVE HEIGHTS vs. DISTANCE FROM EXPLOSION

HR = constant ≈ 110,000

$HR^{.9} = 42,700$

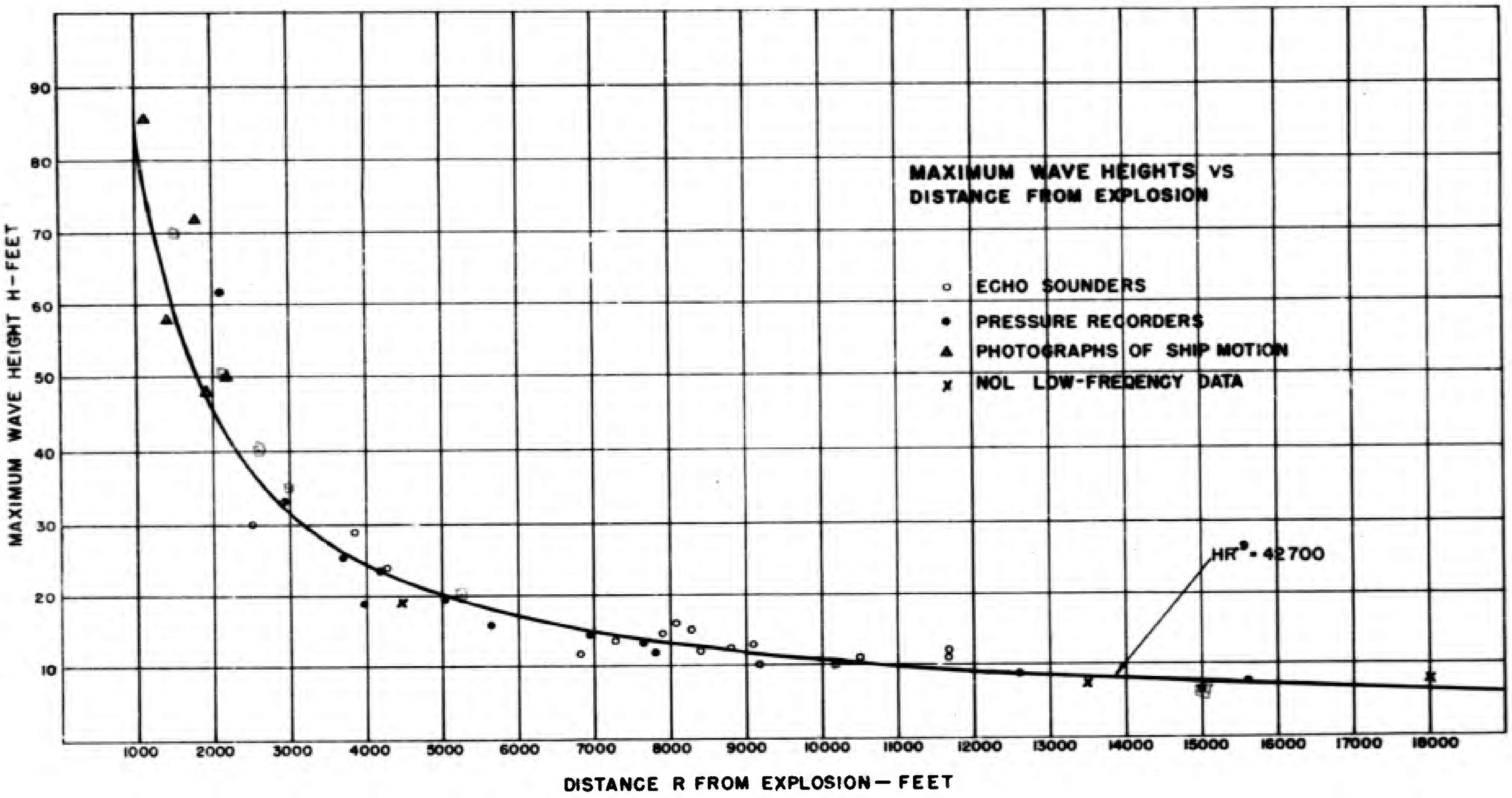

MAXIMUM WAVE HEIGHTS VS
DISTANCE FROM EXPLOSION
○ ECHO SOUNDERS
● PRESSURE RECORDERS
▲ PHOTOGRAPHS OF SHIP MOTION
x NOL LOW-FREQENCY DATA
$HR^{9} = 42700$
MAXIMUM WAVE HEIGHT H-FEET
90
80
70
60
50
40
30
20
10
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
DISTANCE R FROM EXPLOSION — FEET

FIGURE 9

Distances from the target center versus maximum wave height measured from the instrument records are plotted on rectangular coordinates in Figure 9 in order to give a more graphic physical representation of the relationship between maximum wave height and distance. This figure also shows the variability in the waves within a given range from the explosion and indicates the fairly good agreement between bottom pressure and echo sounder records.

Estimated values of the maximum height from trough to crest of the waves which caused the measured vertical displacement of the SARATOGA, the YO-160, the HUGHES, and the LST-133 are also shown in Figures 8 and 9. These estimates were obtained simply by doubling the measured rise for each ship shown in the last column of Table I. This method of estimation is consistent with the instrumental results, which show that the first crest and the succeeding trough are on the average about equal in magnitude. Although these estimates of wave heights under the ships probably represent minimum values it will be seen that on the whole the points lie above the line obtained from the instrument records.

The relationship between maximum wave height and distance was also examined by plotting, in Figure 10, the average heights (from crest to next succeeding trough) of each of the first five waves, against distance from the explosion. It may be seen that the first wave is highest at ranges less than 8000 ft, and that its height decreases linearly with distance, in accordance with the relationship:

$$HR = 94000$$

The maximum wave height in the train following the first wave is seen to pass from the second to succeeding waves in a regular manner. This is directly the result of the fact that when waves are in water deeper than a small fraction of the wave length, the velocity at which energy is transmitted (the group velocity) is less than the velocity of the individual waves (the phase velocity). In the limiting case where the water is deep compared to the wave length, the energy velocity is half the phase velocity. Because the energy travels more slowly than the waves themselves, waves at the rear of the train increase in height at the expense of those in front. As a result, not only does the maximum height pass backward in the train but the number of waves of measurable height becomes larger. At Bikini this number increased from 3 to 2500 ft to more than 14 at ranges greater than 20,000 ft.

Within 8000 ft, for Test B, where the first wave is the highest wave, the relationship, HR equals 94,000, can be used to estimate maximum height at any given distance. Beyond 8000 ft the empirical equation, $HR^{.9}$ equals 42,700, may be employed. The following table gives estimated maximum wave heights at different distances:

Distance (ft)	1000	2000	4000	6000	8000	10,000	12,000
Maximum Ht. (ft)	94	47	24	16	13	11	9

4. Kinematics of the First Crest

The times of arrival of the first wave crest, as recorded by the instruments at different distances from the explosion, are plotted in Figure 11. The estimated times of arrival of this crest under the ships listed in Table I are also shown in the figure. The observed points are very well fitted by a curve which has a slope given by

$$\frac{dR}{dt} = C \quad = \sqrt{g(d+h)}$$

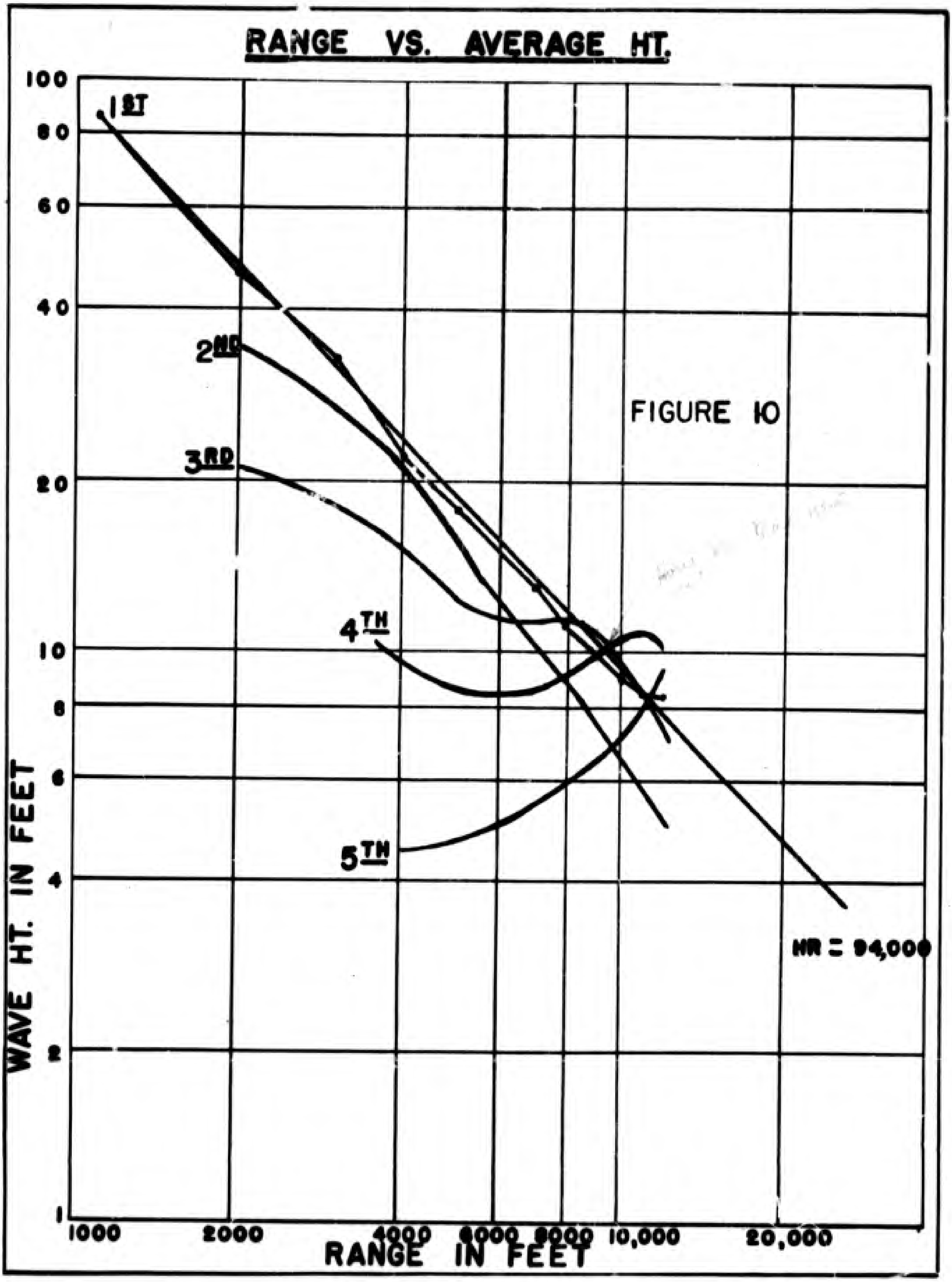

RANGE VS. AVERAGE HT.
100
80
60
40
20
10
8
6
4
2
1
1ST
2ND
3RD
4TH
5TH
HR = 94,000
WAVE HT. IN FEET
1000
2000
4000
6000
8000
10,000
20,000
RANGE IN FEET

FIGURE 10

Here C is the wave velocity, g is the acceleration of gravity, d is the depth and h is the height of the crest above the undisturbed water level. In computing the curve, d was taken as 175 ft, the average depth over the target area, and h was assumed equal to 47,000/R in accordance with the height-distance relationship discussed in the preceeding section. Equation (1) is to a good approximation, the equation for the velocity of a solitary wave.

The following values are obtained for the time of arrival of the first crest at different distances from the explosion:

Distance (feet)	1000	2000	4000	6000	8000	10000	12000
Arrival Time (seconds)	11	23	48	74	101	127	154

Owing to the shoaling of the water in the direction toward Bikini, the velocity of the first wave markedly decreased beyond 12,000 ft and this wave arrived at Bikini, approximately 18,500 ft from the target center, about 306 sec after the explosion. Thus the speed in the last 6000 ft decreased to about half the value near the explosion point.

Times of arrival of the earliest measurable rise of the water surface due to the first wave, when plotted against distance, approximately fit a straight line with a slope of 80 ft/sec, which intersects the abscissa at about 1000 ft. Theoretically the first rise travels with acoustic velocity and is related to the shock wave itself. the measured first rise must therefore represent a sudden increase in an already existing slope of the sea surface and probably related to the rate of travel of wave energy. The point on the back side of the first crest at which one wave surface crosses the undisturbed water level travels at about 70 ft/sec.

As shown in Figure 13 the time interval between the first and the second crests is less than 20 sec at 2000 ft and increases to 40 sec at 12,000 ft. That this interval continues to increase with increasing distance is indicated by the tower photographs from Bikini in which the second major wave arrives at the beach more than 60 sec after the first. It is possible that this apparent increase of 20 sec between 12,000 and 18,000 ft is due to the dying out of the second wave, because of the difference between energy velocity and phase velocity discussed in section 3, above. Further analysis of the photogrammetric results should answer this question.

The distance between the first and second waves at 2000 ft from the target center is 1200 ft. This distance increases with increasing range from the explosion point; at 12,000 ft it is 2800 ft.

It is evident that the time intervals and distances between the first and second crests near the explosion point cannot be regarded as approximating the period and wave length of the first wave, since they are not consistent with the constant and relatively high velocity of the first crest. Indeed, if the first crest is a solitary wave, it has in reality no wave length or period. An effective half wave length and half period for this crest may be arrived at however, by plotting against distance the times of occurrence of the first measurable disturbance and the first subsequent return to the undisturbed water level. This procedure yields a half period and half wave length for the first crest which increases linearly with increasing distance from the explosion in accordance with the relationships: $T = .0019R + a$, and $\frac{1}{2} L = .133 R + b$, where T, L and R represent period, wave length and distance from the target center respectively and a and b are small constants.

The linear increase of effective wave length with increasing distance from the explosion explains the relationship found empirically, that the product of height times radius for the first wave is approximately constant. If the wave form does not change, the energy, E, in a wave radiating from a point source is given by an expression of the form.

$E = KH^2LR =$ constant for any given "shallow water" wave, that is, a wave in which the crest velocity depends only on water depth and wave height and does not vary with period or wave length. But, for the first wave,

$L = mR + b$, where m and b are constants. Hence

$$H^2 = \frac{E}{K(mR + b)R}$$

And

$$HR = \sqrt{\frac{E}{K\left(m + \frac{b}{R}\right)}} = \text{approximately constant when } \frac{b}{R} \text{ is small}$$

compared to m. This is certainly the case beyond a few thousand feet from the explosion point.

5. Kinematics of second and subsequent waves.

In any system of progressive waves where the individual crests maintain their identity and the period, that is the time interval between arrivals of successive crests or troughs, changes from wave to wave the period, T, of a wave travelling with phase velocity $C = \frac{dx}{dt}$ changes with time at a rate

$$(1) \qquad \frac{dT}{dt} = \frac{\partial T}{\partial t} + \frac{\partial T}{\partial x} C$$

To an observer travelling at the group velocity V, that is at the average rate of transfer of wave energy, the wave period remains constant in accordance with the expression:

$V=$

Setting

$$(2) \qquad \frac{\partial T}{\partial x} = -\frac{1}{V}\frac{\partial T}{\partial t}$$

We have, combining (1) and (2)

$$(3) \qquad \frac{dT}{dt} = -\left(\frac{C}{V}-1\right)\frac{\partial T}{\partial t}$$

For a wave system in which all individual waves start at the origin ($t = 0$, $x = 0$), the group velocity, $\underline{V}$ is everywhere given by the expression

$$(4) \qquad V = \frac{x}{t}$$

For water of constant depth the group velocity of an individual wave is a function of $\underline{T}$ only and therefore T remains the same at all points where the ratio $\frac{x}{t}$ is constant. For any given value of T, the quantity $t\frac{\partial T}{\partial t}$ is constant, and in general:

$$t\frac{\partial T}{\partial t} = -g(T)$$

Multiplying both sides of equation (3) by $\underline{t}$ we have:

$$t\frac{dT}{dt} = -\left(\frac{C}{V}-1\right)t\frac{\partial T}{\partial t} = \left(\frac{C}{V}-1\right)g(T)$$

Since, in water of constant depth, $\underline{C}$, like $\underline{V}$, is a function of $\underline{T}$ only,

we have $$\frac{dT}{f(T)g(T)} = \frac{dt}{t}$$

or $$F(T)\,dT = \frac{dt}{t}$$

Integrating both sides between the limits T and T_o and t and t_o respectively

$$\int_{T_o}^{T} F(T)\,dT = \log\frac{t}{t_o}$$

$\underline{T}$ is the period of any individual wave at the time $\underline{t}$, and $\underline{T_o}$ is the period

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TIMES OF ARRIVAL OF FIRST WAVE CREST

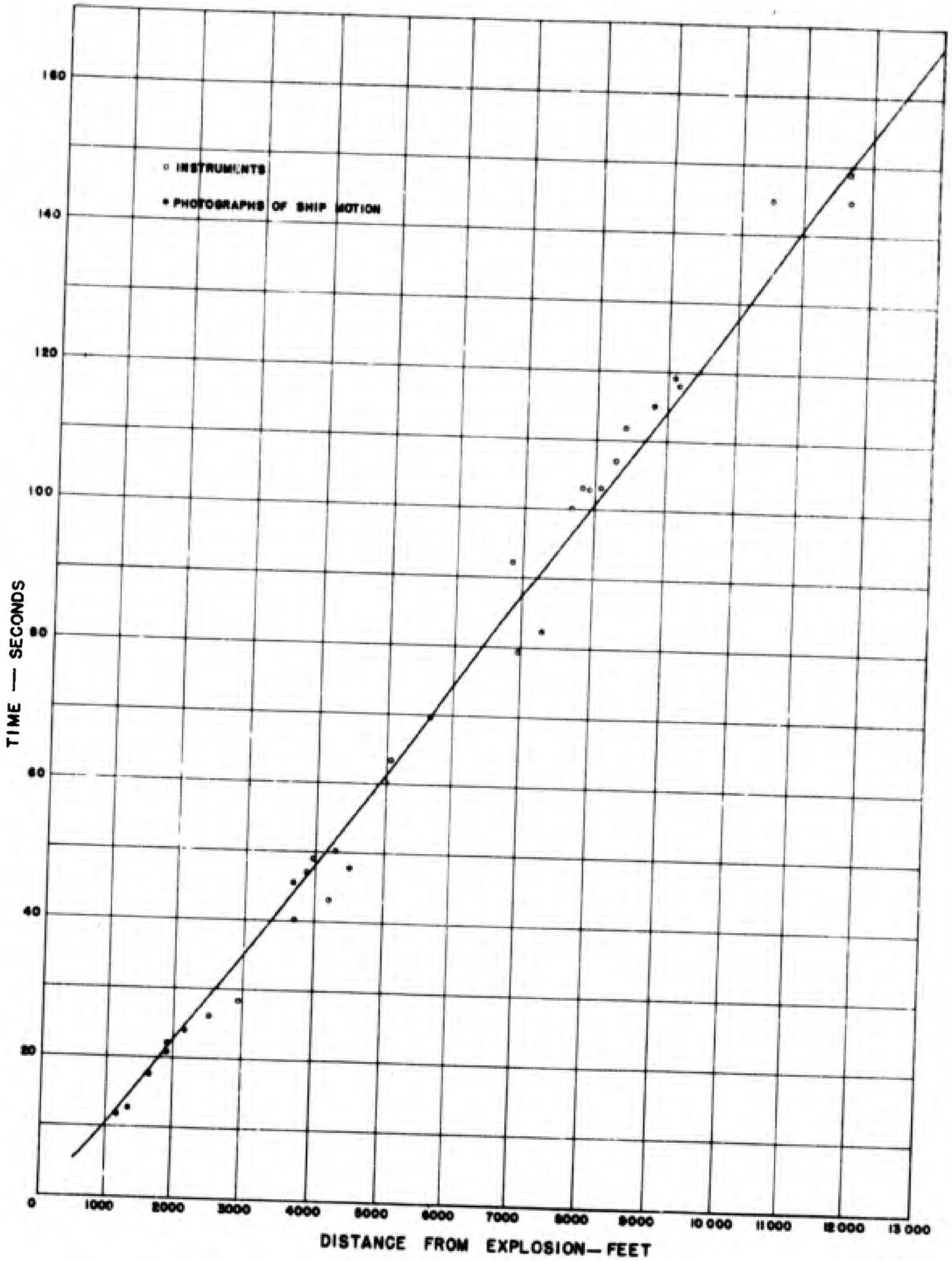
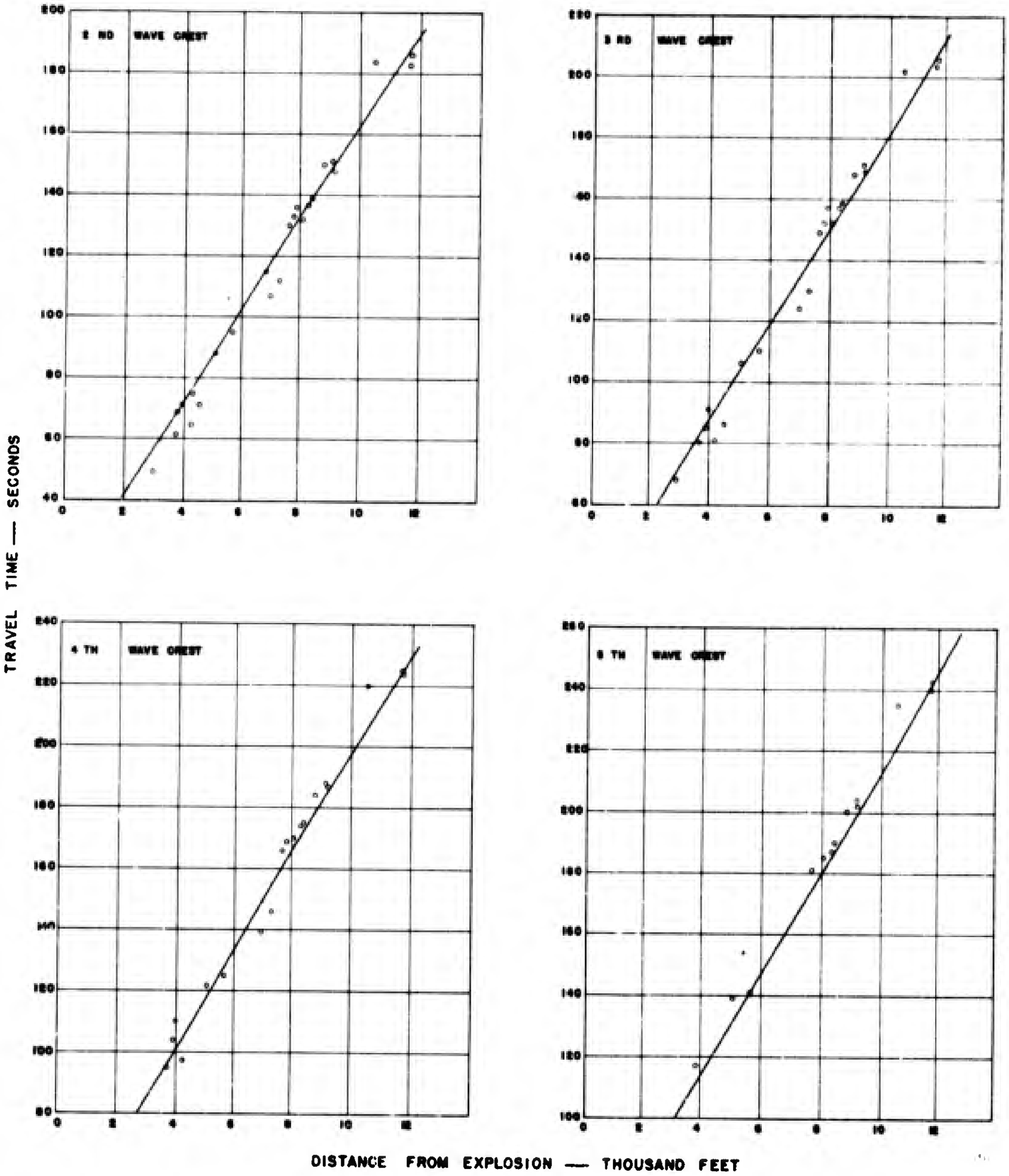


FIGURE 11

FIGURE 12


2 ND WAVE CREST
3 RD WAVE CREST
4 TH WAVE CREST
5 TH WAVE CREST
TRAVEL TIME — SECONDS
DISTANCE FROM EXPLOSION — THOUSAND FEET
200
180
160
140
120
100
80
60
40
220
240
260
0
2
4
6
8
10
12

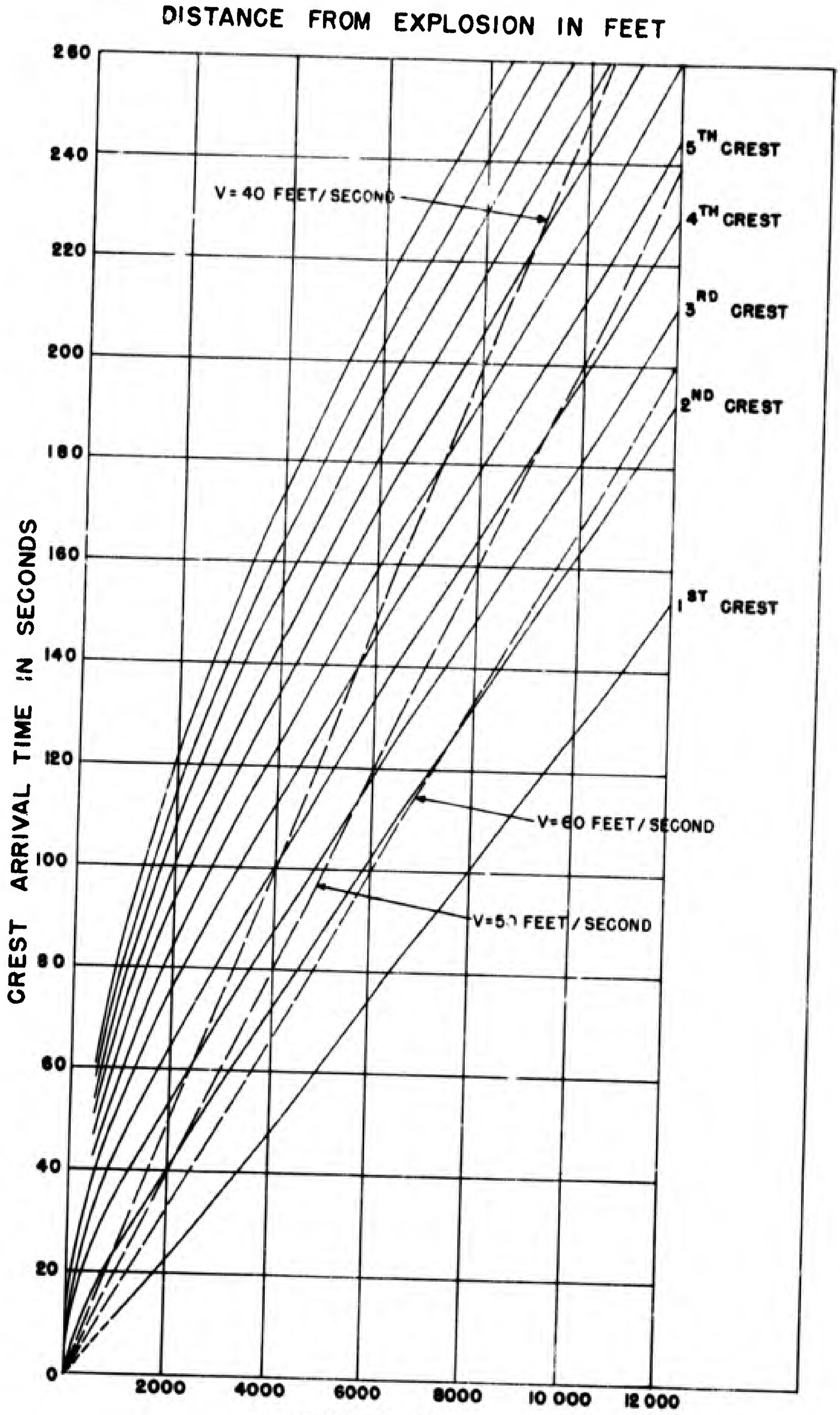


FIGURE 13

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WAVE CHARACTERISTICS— FIRST FIVE CRESTS

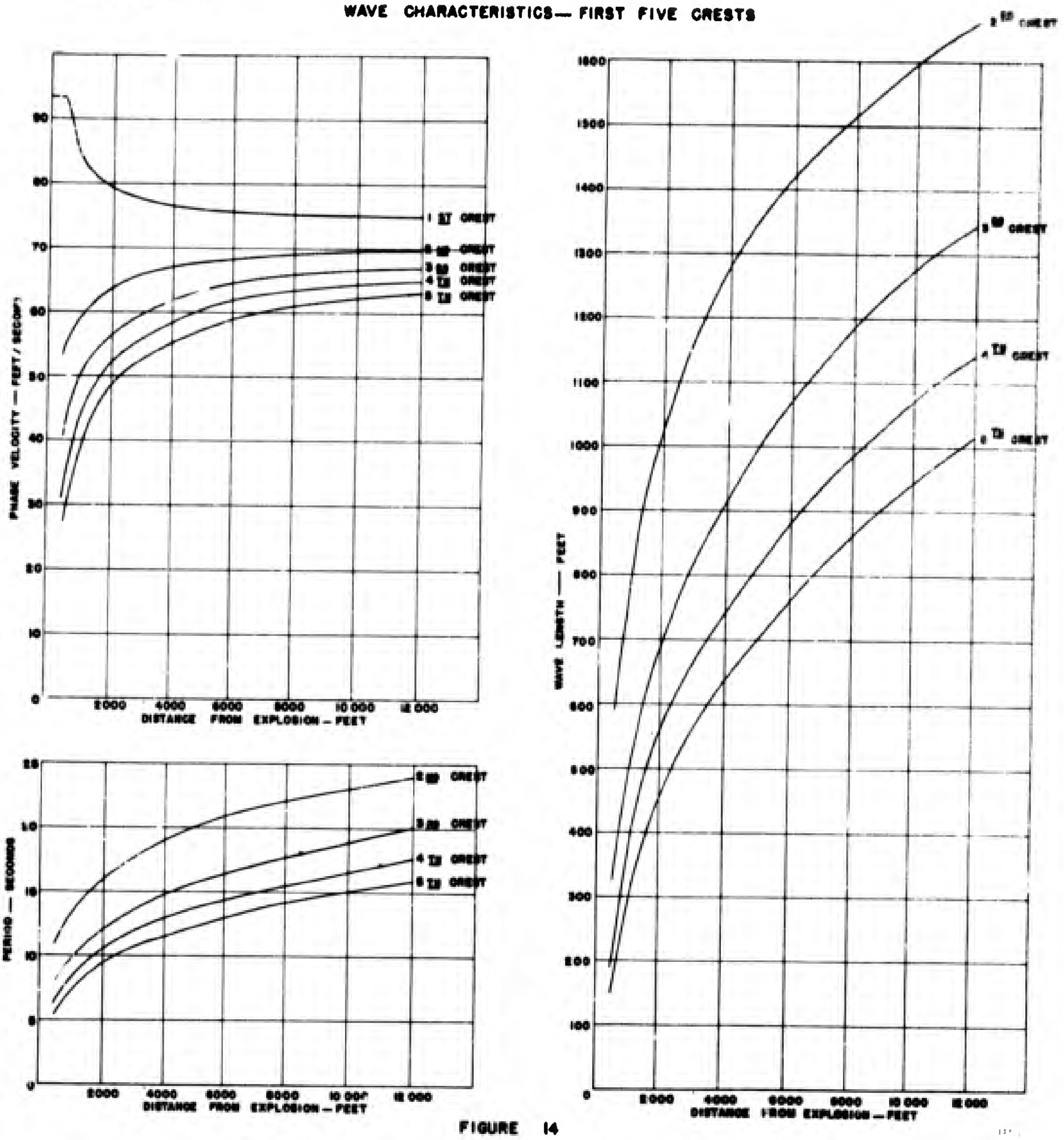


FIGURE 14

of the same wave at the time t_0. Letting the the definite integral equal I (T) - I(T_0) we obtain

$$\frac{e^{I(T)}}{e^{I(T_0)}} = \frac{t}{t_0}$$

Letting $e^{I(T)} = G(T)$ we have

$$(5) \qquad \frac{G(T)}{G(T_0)} = \frac{t}{t_0}$$

The quantity, G(T), can be easily evaluated for water of any known depth, d, at all desired values of period T by the following procedure: The phase velocity and the group velocity are first calculated throughout the desired range of periods using the expression

$$C = \left(\frac{gL}{2\pi} \tanh \frac{2\pi d}{L}\right)^{\frac{1}{2}}$$

$$V = \frac{C}{2}\left(1 + \frac{\frac{4\pi d}{L}}{\sinh \frac{4\pi d}{L}}\right)$$

$$L = CT$$

The quantity $t\frac{\partial T}{\partial t}$ for the same range of period values is obtained numerically from the formula

$$t\frac{\partial T}{\partial t} = \frac{\Delta T}{2}\left(\frac{V_2 + V_1}{V_2 - V_1}\right)$$

and values of the reciprocal of

$$\left(\frac{C}{V} - 1\right) t\frac{\partial T}{\partial t} = \frac{1}{F(T)}$$

are computed. Numerical integration from $T_0 = 1$ to T = T is then carried out using the formula

$$I(T) - I(T_0) = \frac{\Delta T}{2}\Big(F(T_0) + 2F(T_0 + \Delta T) + \cdots\cdot 2F(T_0 + (n-1)\Delta T) + F(T_0 + n\Delta T)\Big)$$

When $T_0 = 1$ and $T_0 + n\Delta T = T$

Values of $G(T) = e^{I(T) - I(T_0 = 1)}$ are tabulated against value of T.

If the time of arrival, t_0, of any particular wave crest or trough at a given point x_0 is known, the group velocity at point x_0 can be obtained from equation (4) and the corresponding period T_0 can be computed. The time, t, at which the wave has any other period, T, is then determined from equation (5) after obtaining the value of G (T) corresponding to T. The group velocity V corresponding to the period T is determined, and the location, x, of the wave at time, t, is obtained from the expression

$$x = Vt$$

According to Kelvin's stationary phase solution of the Cauchy Poisson equation for impulsively generated waves, the value of x^t in deep water is given by

$$(6) \qquad t = \sqrt{\frac{x(8n+1)\pi}{g}}$$

where n is an integer, corresponding to the number of the wave, that is position in the train. Assuming that the waves in the second train at Bikini can be thought of as starting at the origin, they were originally of so short a wave length and period that they behaved like deep water waves in which $C = \sqrt{\frac{gL}{2\pi}}$. Equation (6) can therefore be used to determine the value of t for each crest near the target center.

At greater distances from the explosion point the wave lengths increase so much that the waves can no longer be regarded as deep water waves and equation (6) is not applicable. The times of arrival of each wave crest at different distances from the center must then be computed from equation (5) using as t_o the value obtained from equation (6) for a point near the center. In making the computations, this point was taken as 40 ft.

Figure 12 shows the computed arrival times, at different distances from the explosion, of the second through the fifth crests, compared with observed values. It will be seen that the latter are very well fitted by the theoretical curves. This constitutes one of the most important results of the wave measurement program at Bikini, because it shows that explosively generated waves can be treated kinematically as emanating from a point source in accordance with the Cauchy-Poisson theory.

In Figure 13, arrival times for the first 11 crests at Bikini are plotted together and in Figure 14 computed values of wave length, period and phase velocity for the second through the fifth crests are shown. It will be seen that for any individual wave these quantities all increase with time and distance from the center; and that at any point or time each wave has a period, wave length and velocity less than that of the preceding wave. The period of the second crest increased from 16 to 24 sec between 2000 and 12,000 ft, its wave length increased from 1000 to 1700 ft and the phase velocity increases from 64 to 70 ft. The phase velocity of all crests approached the value $C = \sqrt{gd} \simeq 75$ ft as an asymptote.

All the crests shown in Figure 12 (and succeeding crests not shown) are present as appreciable waves at a considerable distance from the explosion, but at lesser distance only a few waves of measurable height are present. Since the wave energy travels with group velocity $V \simeq x/t$, the only measurable waves present at any given distance are those that have attained or exceeded a minimum group velocity which is determined by the size of the initial disturbance. At Bikini this group velocity was about 40 ft/sec. Since the average wave length between any two lines of constant group velocity remains the same at all distances from the explosion, while the distance between these lines increases linearly, the number of waves present increases in direct proportion to the time or the distance.

The highest wave in the train always has the same group velocity, which at Bikini was about 53 ft/sec. Succeeding crests become highest as they attain this group velocity (and the corresponding wave length and period). Since the group velocity lines spread linearly with increasing distance from the explosion the energy per unit area decreases in proportion to the square of the distance, and the height of the highest wave in the train should therefore be approximately inversely proportional to the distance.

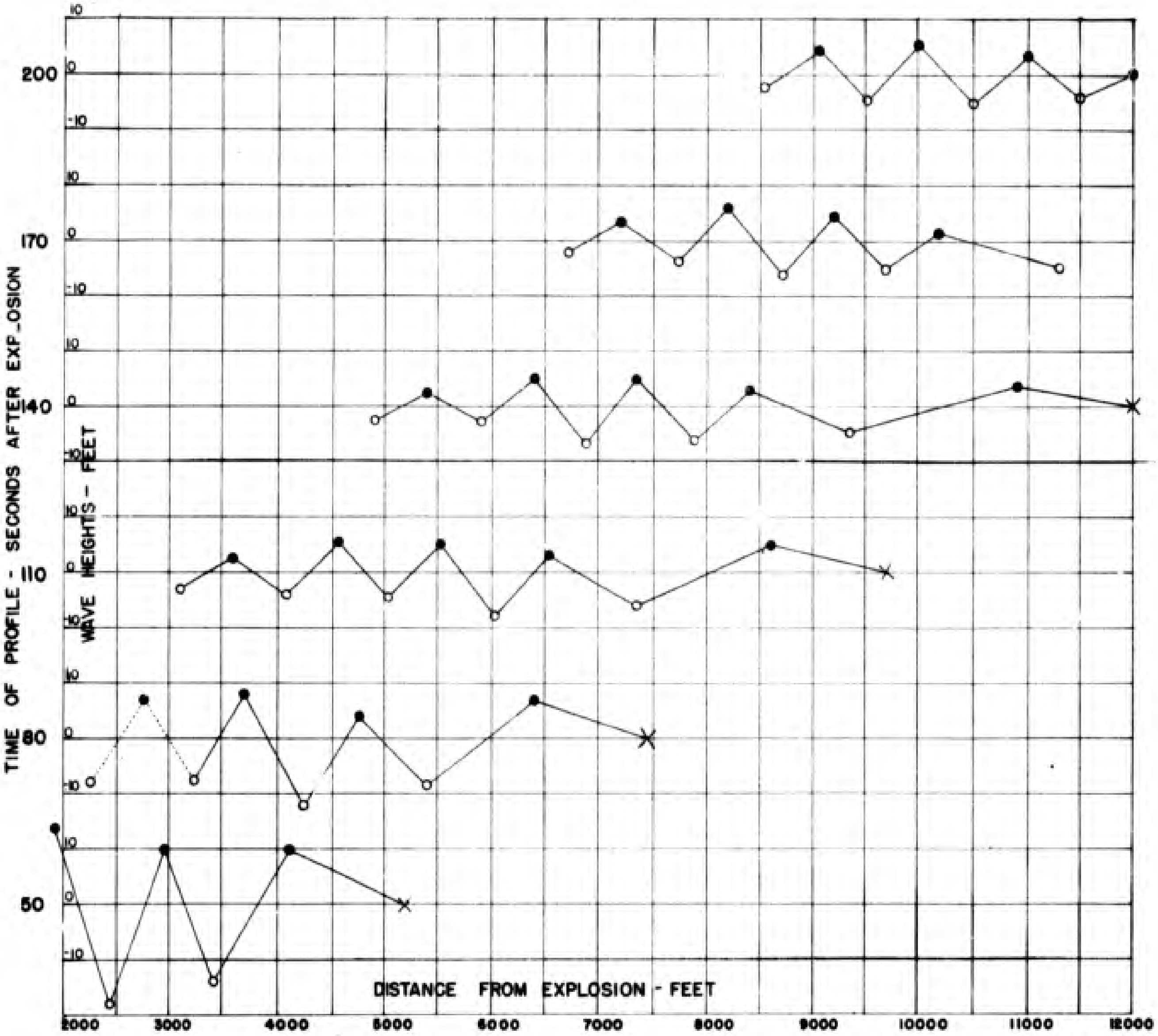
6. Origin of Waves.

In all its characteristics the first wave behaves differently from the succeeding ones. It may be thought of as a long solitary wave, generated directly by the explosion, and receiving its initial energy from the high-velocity outward motion of the water. The subsequent waves are probably generated impulsively by the collapse of the hole blown in the water.

The very small number of measurable waves near the explosion point shows that the amplitude of the central oscillation diminished rapidly with time. According to the Cauchy-Poisson theory, the central mount subsided to the undisturbed lead without further oscillation.

7. Wave Shape.

The profile of the water surface on a given radius from the bomb at any instant after the explosion could be obtained directly from the records if sufficient observation were available. Only an approximation



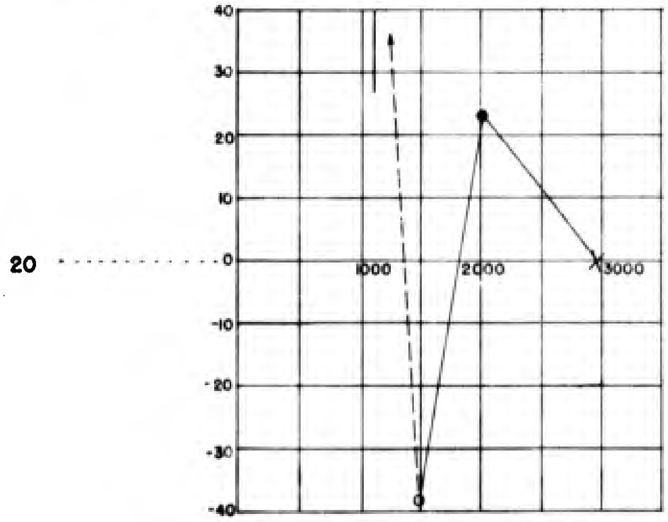


FIGURE 15

PROFILE OF TRAIN
OF FIRST WAVES
AT 30 SECOND INTERVALS

to wave shape can be deduced from the data at hand. Generalized profiles at 30 sec intervals for times between 20 and 200 sec after the explosion are shown in figure 15. It may be seen that when the first crest was 2000 ft from the target center the average slope from the undisturbed water to the crest was $\overset{.0232}{1^\circ\,19'}$. The slope between the first crest and the adjacent trough was $\overset{.12}{6^\circ\,51'}$. At 140 sec the first wave crest had progressed out to nearly 11,000 ft while the fifth crest was at 5500 ft. The leading edge of the first wave was at 12,000 ft, and the average slope from this point to the first crest was $\overset{\theta = .0021}{0^\circ\,12'}$. The highest average slope from trough to crest was 1° 23', on the forward side of the fourth wave.

$H/\lambda = .0058$

.06

$H/\lambda = 5170$

From the present data, wave profiles prior to 20 sec are very uncertain. Such a profile near zero time, drawn from the extrapolated positions of the first disturbance and the first crest and trough suggests that the outer side of the first crest had an average slope of about 15° while the inner slope was apparently very much steeper. Waves are unstable and break when the average slope from trough to crest much exceeds 15°; hence the first wave was probably breaking as it left the central area.

8. Wave Energy.

Figure 15 shows that at a time 140 sec after the burst there were present only 5 waves high enough to be recorded by the instruments. This system of high waves covered the area between 4600 and 12,000 ft. From the aerial and tower photographs, which show over 20 waves, it is evident that waves too small to detect existed inside of 4600 ft at

Since Wave energy is proportional to the square of the height, however, the major part of the total energy of the waves produced by the bomb must have been contained in the first 5 waves at 140 sec. At times later than 140 sec more than 5 waves of detectable height were present simultaneously owing to the gradual dilution of the total wave energy among an increasingly large number of waves.

If the wave form is sinusoidal the energy in a single wave radiating from a point source is given by the following equation:

$$E = \frac{\pi}{4} \overset{2}{\rho} g H^2 LR \qquad \text{where L is wave length.}$$

Using this equation, the total energy in the first 5 waves was found to be 3.4 times 10^{18} ergs or about .4% of the total energy of the bomb assuming an equivalent weight of 20,000 tons of TNT. If the wave profiles approach a triangular form rather than a sinusoidal one, the wave energy can be computed directly from Figure 15 by measuring the displacement, h, of the free surface for a time of 140 sec at 100 ft intervals from 4600 to 12,000 ft and integrating numerically using the expression:

$$E = 200 \pi \rho g \sum_{R = 4600}^{R = 12000} R h^2$$

This procedure gave a value of 2.6 time 10^{18} ergs or about .3% of the total energy of the bomb. The true value for the energy of the first 5 waves probably lies between these limits, depending on the actual wave form. More than half of this energy was in the first wave.

9. <u>Model laws for water motion resulting from shallow water explosion</u>:

For a considerable distance from the explosion, the first wave is the highest wave. The model or scaling law for the relationship between the height of this wave, it's distance from the explosion and the charge weight can be deduced from energy relationships, if it is assumed that the fraction of the explosive energy which goes into wave formation is constant, that is:

(1) $E \propto W$, where E is the energy in the wave and W the charge weight. Both the Bikini and the model experiments show that for any given charge weight, the product of the height of the first wave times the distance from the explosion is a constant:

(2) $HR = C$

and, as indicated above:

(3) $E = \frac{\pi}{4}\rho g H^2 LR \propto W$

Substituting for H from equation (2) and solving for L:

$$L = \frac{4ER^2}{\pi\rho g C^2 R} = mR, \quad m = \text{Constant for any given charge weight}$$

therefore, $E = \frac{\pi}{4}\rho\, gH^2 mR^2 \propto W$

and $H^2R^2 = \frac{4E}{\pi\rho gm} \propto W$ over the range of conditions in which m is constant.

(4) $HR = K(W^{\frac{1}{2}})$ $K = \text{Constant}$

$$\text{and } \frac{H_1R_1}{H_2R_2} = \frac{W_1^{\frac{1}{2}}}{W_2^{\frac{1}{2}}}$$

If distance R is taken proportional to the cube root of the charge weight, that is: $R \propto W^{1/3}$ then

$$\frac{R_1}{R_2} = \frac{W_1^{1/3}}{W_2^{1/3}}$$

and the ratio of wave height H_1 at distance R_1 for weight of charge W_1 to height H_2 at distance R_2 for charge weight W_2 is:

$$\frac{H_1 W_1^{1/3}}{H_2 W_2^{1/3}} = \frac{W_1^{\frac{1}{2}}}{W_2^{\frac{1}{2}}}$$

$$\frac{H_1}{H_2} = \frac{W_1^{1/6}}{W_2^{1/6}}$$

Similarly, if the distance is taken proportional to the fourth root of the charge weight: $R \propto W^{1/4}$, THEN $\frac{R_1}{R_2} \quad \frac{W_1^{1/4}}{W_2^{1/4}}$ and

$$\frac{H_1}{H_2} = \frac{W_1^{1/4}}{W_2^{1/4}}$$

A similar result can be obtained if, as shown for explosions in deep water, all linear dimensions are proportional to the radius of the central bubble or cavity produced by the explosion, and if it is assumed that the energy of the cavity is proportional to charge weight, for the optimum situation when the bubble is just under the surface, the energy of the bubble:

$$(5) \quad E_{\text{bubble}} = \frac{4}{3}\pi r^3 \rho g (r + z) \propto W$$

where r is the radius of the bubble and z is the head of water corresponding to atmospheric pressure. For two charge weights W_1 and W_2:

$$\frac{r_2^3 (r_2 + z)}{r_1^3 (r_1 + z)} = \frac{W_2}{W_1}$$

When W_2 is large and W_1 is small, r_1 is negligible compared to z, and z is negligible compared to r_2;

$$\frac{r_2^4}{r_1^3} = \frac{z W_2}{\text{[illegible]}}$$

or $$\frac{r_2^4}{r_1^4} = \frac{z W_2}{r_1 W_1}$$

$$(6) \quad \frac{r_2}{r_1} = \frac{(z)^{1/4}}{(r_1)} \quad \frac{(W_2)^{1/4}}{(W_1)^{1/4}} = \frac{n(W_2^{1/4})}{(W_1^{1/4})}$$

n = Constant for any W_1

Therefore, since all linear dimensions are assumed proportional to bubble radius:

$$\frac{H_2}{H_1} = \frac{R_2}{R_1} = \frac{r2}{r_1} \quad \frac{n(W_2)^{\frac{1}{4}}}{W_1^{\frac{1}{4}}} \qquad p,q = \text{Constants}$$

$$\frac{H_2R_2}{W_2^{\frac{1}{2}}} = \frac{H_1R_1}{W_1^{\frac{1}{2}}} \frac{n^2}{pq} = K$$ Since W_1 can be any arbitrary small charge

(4) $HR = K(W)^{\frac{1}{2}}$

Prior to Test B a series of model tests of explosions in shallow water were carried out under the direction of Dean M.P. O'Brien and Professor J. W. Johnson of the University of California at the Woods Hole Oceanographic Institution, at the Naval Mine Warfare Test Station and at the David Tayor Model Basin. Similar tests were carried out at U.S. Navy Electronics Laboratory, San Diego. In the tests, the depth of water was varied in proportion to the cube root of the charge weight and was scaled from the expected conditions for Test B on the assumption that the depth at Bikini would be 180 ft and the equivalent charge weight of the bomb would be 20,000 tons of TNT. The results of the model studies are plotted on Figure 16 together with the points read off the experimental curve for maximum wave height versus range in Test B. From this figure it can be seen that all the points are very well fitted by the equation:

(7) $\frac{H}{W^{\frac{1}{4}}} \quad \frac{R}{W^{1/3}} = 4.2$

Attempts to plot $\frac{H}{W}1/6$ against $\frac{R}{W}1/3$ or $\frac{H}{W^{\frac{1}{4}}}$ AGAINST $\frac{R}{W^{\frac{1}{4}}}$ both gave considerable more scatter between the model values and the prototype. The empirical model relationship can be expressed in the form:

(7) $HR = 4.2\ W^{1/12}\ W^{\frac{1}{2}}$

It is believed, that the discrepancy between this empirical relationship and the theoretical model law given above can be partly explained by the fact that both the models and the prototype were carried out in shallow water, (shallow in terms of equivalent charge radii) in which the depth was scaled as the 1/3 power of the charge weight. Model studies carried out by the SEAL Project in New Zealand show that under these conditions the product of height-times radius increases more rapidly than the square root of the charge weight. In the New Zealand experiments it was found that to a first approximation:

$$(8) \qquad \frac{HR}{H_oR_o} = a\left(\frac{D}{L_o}\right)$$

where the subscript o denotes the deep water value and L_o is proportional to $W^{\frac{1}{4}}$. For the Crossroads data:

$$(9) \qquad \frac{D}{L_o} \propto \frac{W^{1/3}}{W^{\frac{1}{4}}} = W^{1/12}, \text{ that is, } \frac{D}{L_o} = bW^{1/12}$$

hence, $\dfrac{HR}{H_oR_o} = ab\,W^{1/12}$

and, $H_oR_o = \dfrac{HR}{ab\quad W^{1/12}}$

substituting for HR,

$$(10) \qquad H_oR_o = \frac{4.2\ \ W^{1/12}W^{\frac{1}{2}}}{ab\ W^{1/12}} = K_oW^{\frac{1}{2}},$$

in agreement with the theoretical scaling law for large charges in deep water.

whence, $K_o = \dfrac{4.2}{ab}$

according to the New Zealand data $L_o = 16W^{\frac{1}{4}}$ and at Bikini and in the Crossroads model studies $D = .52\ W^{1/3}$ so that $b = .0325$. In the New Zealand studies $a = 2.2$ when $0 < \dfrac{D}{L_o} < 0.22$. Substituting, $ab = .072$ and

No No

MODEL LAW FOR EXPLOSION WAVES IN SHALLOW WATER

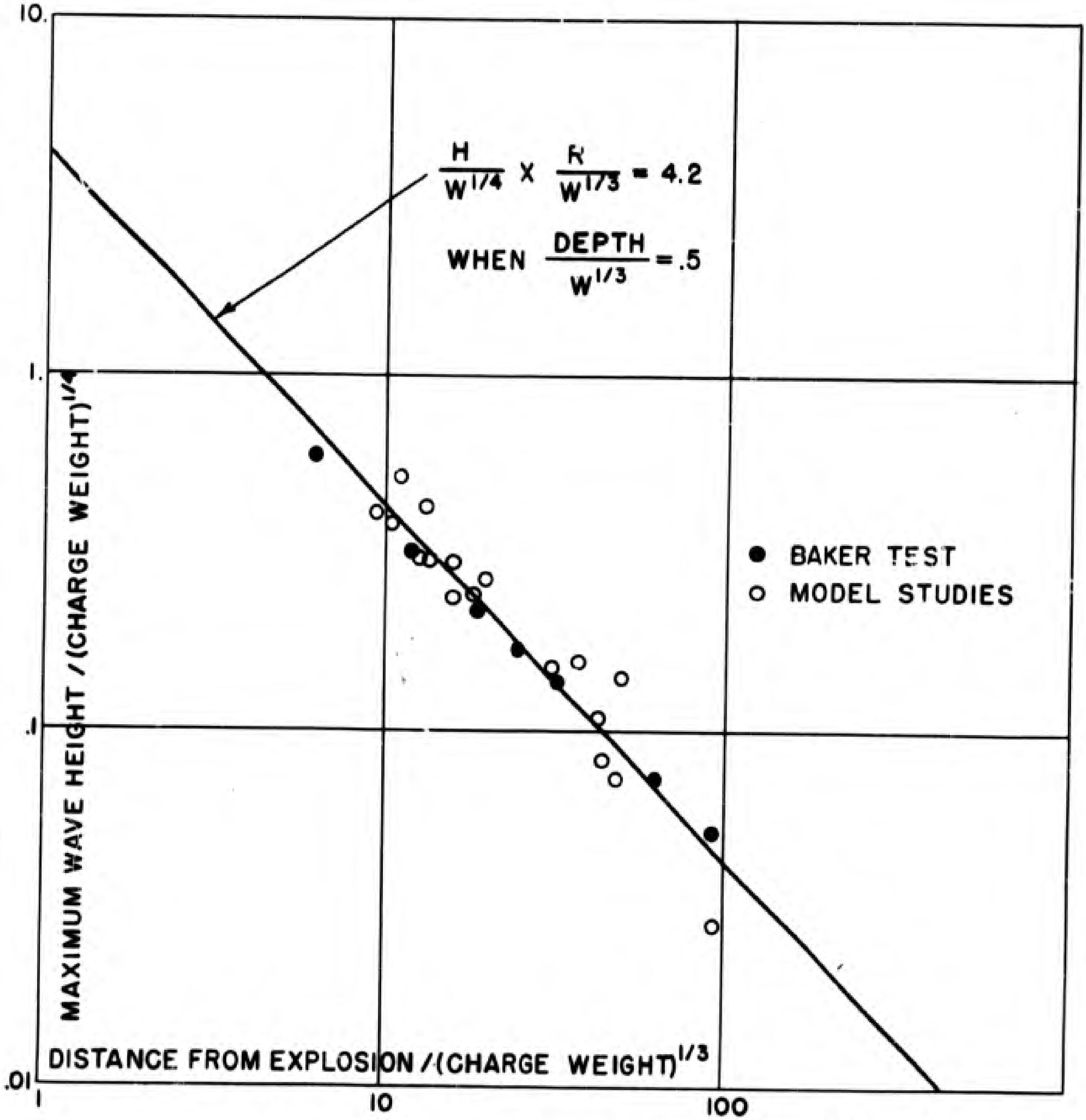
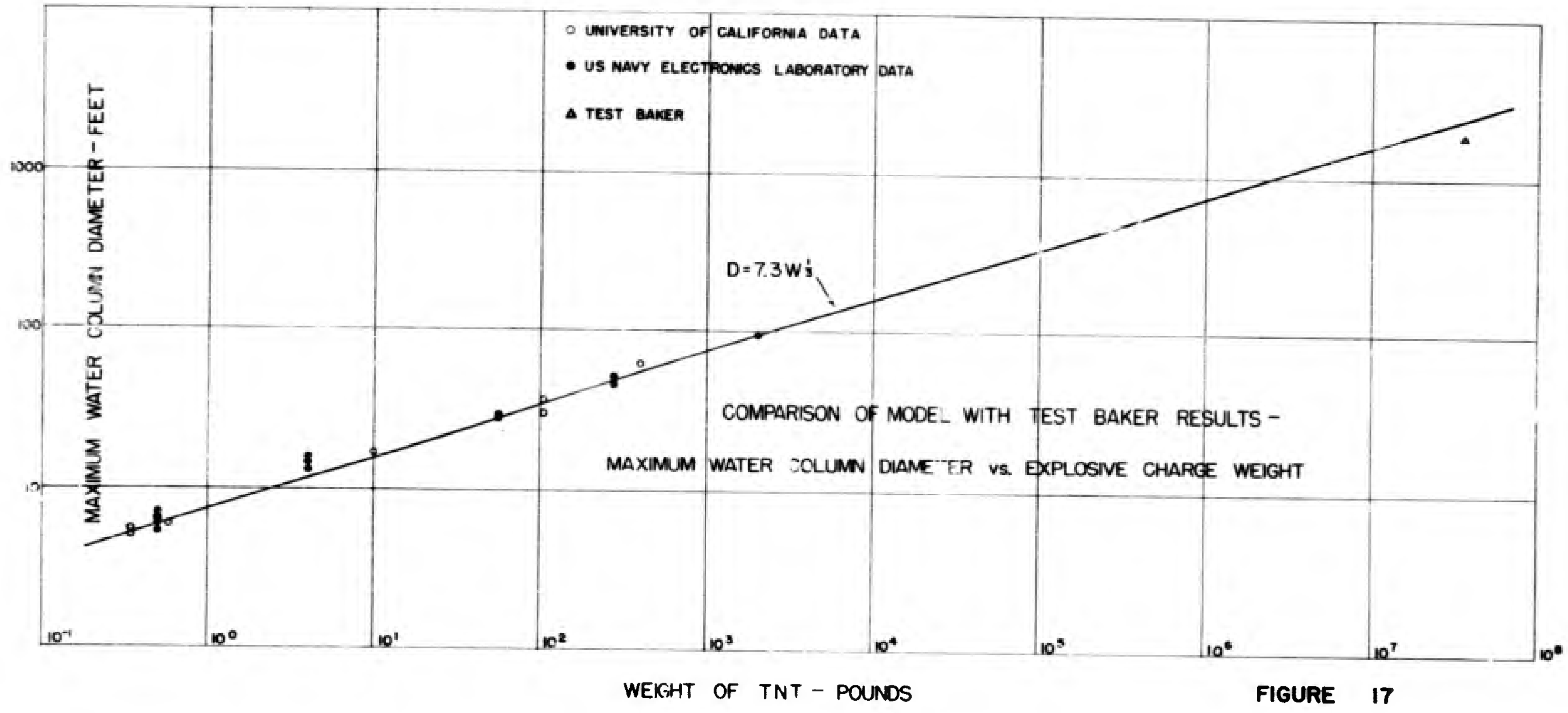


FIGURE 16


COMPARISON OF MODEL WITH TEST BAKER RESULTS -

MAXIMUM WATER COLUMN DIAMETER vs. EXPLOSIVE CHARGE WEIGHT

FIGURE 17

$K_o = 59$, therefore:

(11) $H_oR_o = 59\ W^{\frac{1}{2}}$

For large charges at the water surface in deep water, the New Zealand experiments indicate that K_o is about 30, roughly half the value computed from the Test B data. Dr. Penney in his memorandum discussing the optimum depths for Test C gives estimated figures for wave height corresponding to an average value of 45 for K_o for charge weights from 8 to 50 kilotons, Penney's computations are based on a measurement made at the U.S. Navy Electronics Laboratory, San Diego, of wave heights from 200 lb of TNT, 20 ft below the surface in 180 ft of water.

Although the discrepancy between the empirical and theoretical scaling laws can be formally resolved by the considerations just given, there is some reason to believe that even if depth were scaled to the $\frac{1}{4}$ power of the charge weight the same empirical relationship would still be found. Depths scaled to the $\frac{1}{4}$ power of the charge weight were employed in some of the Crossroads model tests and these appear to fit the curve of Figure 16 reasonably well. Moreover, in the New Zealand experiments it was found that K_o increased by a factor of at least 2 with large increases in charge weight. Thus, big charges seem to have, in effect, a greater efficiency in producing waves, or alternatively, more of the energy available for wave formation may go into the first wave when the charge weight is increased, or the ratio of wave length to distance may decrease with increasing charge weight.

In the Crossroads model studies of water motion resulting from explosions in shallow water the characteristics of the water column were investigated in addition to surface water wave phenomena.

It is difficult to deduce a scaling law for the height of the column because of the widely differing relative importance of air resistance and gravity in model and prototype. In the former, air friction is the principal force resisting the upward motion of the column, while in the prototype the role of gravity is greatly increased.

Unlike the column height, it should be expected that to a first approximation the diameter will be proportional to the cube root of the charge weight, since the similarity law for explosions in a homogeneous medium under uniform pressure states that the same pressure and the same induced mass velocity should occur at distances and times which are proportional to the cube root of the charge weight. That this expectation is justified is indicated in Figure 17, where maximum water column diameter for the model data and the Test B prototype is plotted against charge weight. In the model studies the maximum diameter was approached at a time between .007 $W^{1/3}$ and .03 $W^{1/3}$, corresponding to 2.3 to 9.9 sec for Test B, if an equivalent charge weight of 35 million pounds is assumed. The photogrammetric measurements from one of the Bikini towers show that at 10 sec the diameter is 1700 ft and at 12 sec it is about 1900 ft. The latter value is plotted in figure 17.

The line of best fit drawn through the model points corresponds to the equation D equals 7.3 $W^{1/3}$. This would give a diameter of 2500 ft for an assumed equivalent weight of 40 million pounds, or, alternatively an equivalent weight of 18 million pounds for the measured diameter.

The discrepancy between the measured column diameter for Test

B and the expected value is about at the limit of the variability shown by the model points. This deviation from similarity may be due to differences in the shape of the cavity resulting from the fact that variations in hydrostatic pressure from surface to bottom in the prototype are larger in proportion to the explosive pressure than in the model.

10. Wave Phenomena in Shallow Water

The previous discussion has concerned waves travelling in water of essentially constant depth. As the waves entered shallow water several changes took place. These were most fully observed off Bikini by means of aerial and tower photography, the electric contactor beach poles, and the tin can height indicators. The principal change in wave characteristics was the marked increase in height compared to the height which would be expected at the same distance if the depth of water had remained constant. From Figure 8 it can be seen that the deep water height-distance relationship would give a maximum height at Bikini, 18,000 ft from the explosion, between 6 and 7 ft. The tower photographs show that the first wave was 15 ft high at the instant of breaking, and this value is confirmed by the tin can and electric contactor poles, which show heights of 11 to 14 ft above the undisturbed water level at points on the beach some distance from the water line.

This increase in wave height must have been accompanied by a decrease in the effective wave length. Qualitative evidence for decrease of wave length in the second and later waves was obtained from preliminary inspection of the aerial photographs, which show a continually decreasing length from the time that the waves first encountered a change of bottom slope to the time of breaking on the beach. The amount of decrease in the wave length of these waves can be demonstrated as follows: The times between arrivals, of each of the major crests after the first, average about 16 sec. Since the average period of these waves in deep water is about 17 sec, it is evident that little change in period occurred in shallow water. On the other hand, as was shown in Section 5, the velocity must have been proportional to the square root of the depth. Thus, the wave length which equals the product of velocity times period likewise decreased in proportion to the square root of depth.

The considerations given in Section 5 concerning the relationship between wave length, height, and energy show that at a constant radius the height is inversely proportional to the square root of the wave length, thus the ratio of height in shallow water to height in deep water, for waves later than the first, must be inversely proportional to the fourth root of the ratio of shallow water to deep water depth.

The first crest arrived at Bikini and commenced to break in front of the North tower about 306 sec after the explosion. The second crest commenced to break over 60 sec later; the time interval between the first and second crests which had increased to 40 sec 12,000 ft from the target center, continued to increase with increasing distance. From the following considerations it can be inferred, however, that the effective wave length of the first wave decreased in proportion to the square root of depth. Photogrammetric measurements indicate that this wave started to break 390 ft off Bikini. From a survey conducted before the test the depth at this point was found to be 20 ft. The fourth root of the ratio of shallow to deep water depths is .58, taking a deep water depth of 170 ft. From this value the ratio of shallow to deep water wave height is 1.7. Extensive observational data on breaking waves demonstrates that the height of a breaking wave is about 30% greater than it would be if the wave were not breaking. (These data also show that waves break in shallow water when the depth is about 1.3 times the height of the breaker.) Thus the ratio of height at breaking to deep water height for the first wave from Test B becomes 2.3 if it is assumed that the effective wave length decreased in proportion to the square root of depth. The theoretical height at breaking is 2.3. times 6.5 or 15 ft, in exact agreement with the observed value.

Figures 18 portray the arrival of the first wave at Bikini. Figure 18 shows the wave shortly after it started to break at the outer edge of the diving raft in front of the north tower (the later waves pushed this raft against the three electric contactor poles which can be seen in the figure, demolishing them.) Figure 19 shows the complete breaking of the first crest on the beach. In these two figures a tin can recorder pole can be seen between the left hand native hut and the painted tree to its left. The uprush from the wave undercut the beach and washed this instrument away as can be seen in figure 20 which also shows the uprush of water over the basketball court at the right of the figure. This court, which had a height above the undisturbed water level of 17 ft, was later found inundated and covered with debris. A reflected wave is seen leaving the beach in Figure 20; this wave was also detected by the bottom pressure recorders farther from shore.

Appreciable amounts of beach material were washed out into the lagoon by the backwash from the breakers. This material, and that stirred up from the bottom, is visible in many of the aerial photographs clouding the water to a considerable distance off the beach. Erosion of the beach was plainly evident from an examination on the afternoon of Baker Day. Some beach material was also carried inland, the farthest debris line in the region of the photographs being about 200 ft from the shore.

11. Wave Damage to Ships:

Fairly unequivocal evidence for major damage to the SARATOGA due to wave action is obtainable in the series of photographs taken at three second intervals from one of the Enyu towers. Figure 21 is a photograph of the target array taken from Enyu just after the explosion but before any visible shock effect had reached the SARATOGA. Both the island structure and the radar mast are undamaged at this time. Figure 22, which was taken 9 seconds later, shows the radar mast bent over but the island as yet unaffected. Although the shock wave was sufficient to damage the antenna it apparently was not strong enough visibly to affect the island. Comparison of this view with figure 21 shows the stern of the SARATOGA rising on the first wave crest, high (measured as at least 43 ft) above the top of the bow of the APA formerly in line with her flight deck. Shortly after the photograph reproduced in figure 22 was taken, the ship was obscurred from view by the base surge. Figure 23, taken well after major waves and other effects subsided, shows the central part of the island structure folded down onto the deck of the carrier. It appears probable that shortly after the rise shown in Figure 22 the SARATOGA fell into the succeeding trough and was badly hit by the second wave crest. That wave action was the probable cause of this damage, rather than the outward expansion of the water column, is evident from photogrammetric measurements which show that the vertical portion of the water column was never closer than 200 ft to the midships section of the SARATOGA. The splashing up and out from the surface, of water falling out of the column is not ruled out, however, as the responsible phenomenon.

FIGURE 18 - FIRST WAVE COMMENCING TO BREAK OUTSIDE SWIMMING PONTOON. AT THIS POINT THE CREST WAS FIFTEEN FEET HIGH.

FIGURE 19 - FIRST WAVE BREAKING ON BIKINI BEACH.

FIGURE 20 - UPRUSH OF FIRST WAVE ONTO BASKETBALL COURT.

FIGURE 21 - VIEW FROM ENYU IMMEDIATELY AFTER EXPLOSION SHOWING SARATOGA IN UNDISTURBED POSITION.

FIGURE 22 - VIEW FROM ENYU 10 SECONDS AFTER EXPLOSION SHOWING STERN OF SARATOGA RISING 43 FEET ON FIRST WAVE CREST. NOTE THAT STACK APPEARS UNDAMAGED.

FIGURE 23 - VIEW FROM ENYU 10 MINUTES AFTER EXPLOSION SHOWING STACK OF SARATOGA FOLDED DOWN ON DECK

GEOLOGICAL EFFECTS OF TEST BAKER

1. Beach Erosion From Waves:

Since the bomb waves were expected to break at Bikini with a height considerably greater than that of any breakers normally existing in the lagoon it was thought that appreciable beach erosion might result from Test B. Measurements of the extent of such erosion from a small number of waves of known height would be valuable in contributing to an understanding of shore line processes and might aid prediction of the beach damage to be anticipated from a bomb exploded within a few thousand feet of the shore.

Transverse profiles spaced about one-quarter of a mile apart were measured across the lagoonward beach of Bikini Island and the adjoining reefs to the north and south, as a basis for estimating beach erosion. Since beaches ordinarily show some variation througnout the monthly tidal cycle, these profiles were re-measured 5 or 6 times between March and September. The repeated measurements showed that the normal variation to be expected is much less than 12 in.

A preliminary comparison was made between the last set of measurements taken before B Day, on July 6, and measurements taken afterward on B Day plus five days, July 31. Most of the profiles showed normal tidal cycle variations of beach level. That some changes in these areas, though small, did result from the bomb waves was indicated by the presence of a thin deposit of beach sand reaching 25 to 100 ft inland from the beach. This sand obvously was eroded from the beach and transported inland by the bomb waves. The erosion of the beach was intense enough to cause a definite change in the beach profile on the spit northwest of Bikini Island. Two sets of profiles from this spit are shown in Figure 24. The greater change by far is shown by the westernmost set, where a prism of sand 30 ft wide and up to 70 in thick was removed. This sand had clearly been carried over the spit and deposited as a broad fan on the seaward side.

No obvious change in composition or grain size of the beach sand resulted from the waves.

In the process of eroding the beach, the waves set up by the bomb shifted large blocks of beach rock measuring up to nine by five by one feet in size. Many of these slabs showed fresh scars several inches across, some were overturned, some broken across, but none, so far as could be determined, were carried more than a few feet from their original positions.

2. Bottom Topography

In order to determine the dimensions of the crater produced by the explosion a large number of fathometer lines were made in the vicinity of the bomb site before and after B Day. Figure 25 shows the pre-B Day soundings and Figure 26 the post-B Day ones. Contours at ten foot depth intervals were drawn on both charts using both sets of soundings in the outlying areas where there seemed to be no great conflicts of data. Some small differences are present there but these are probably the result of slightly inaccurate positions. Nearer the bomb site differences between both sets of soundings were found which were clearly too great to be ascribed to inaccurate positions, and in these areas different sets of contours were drawn for each chart.

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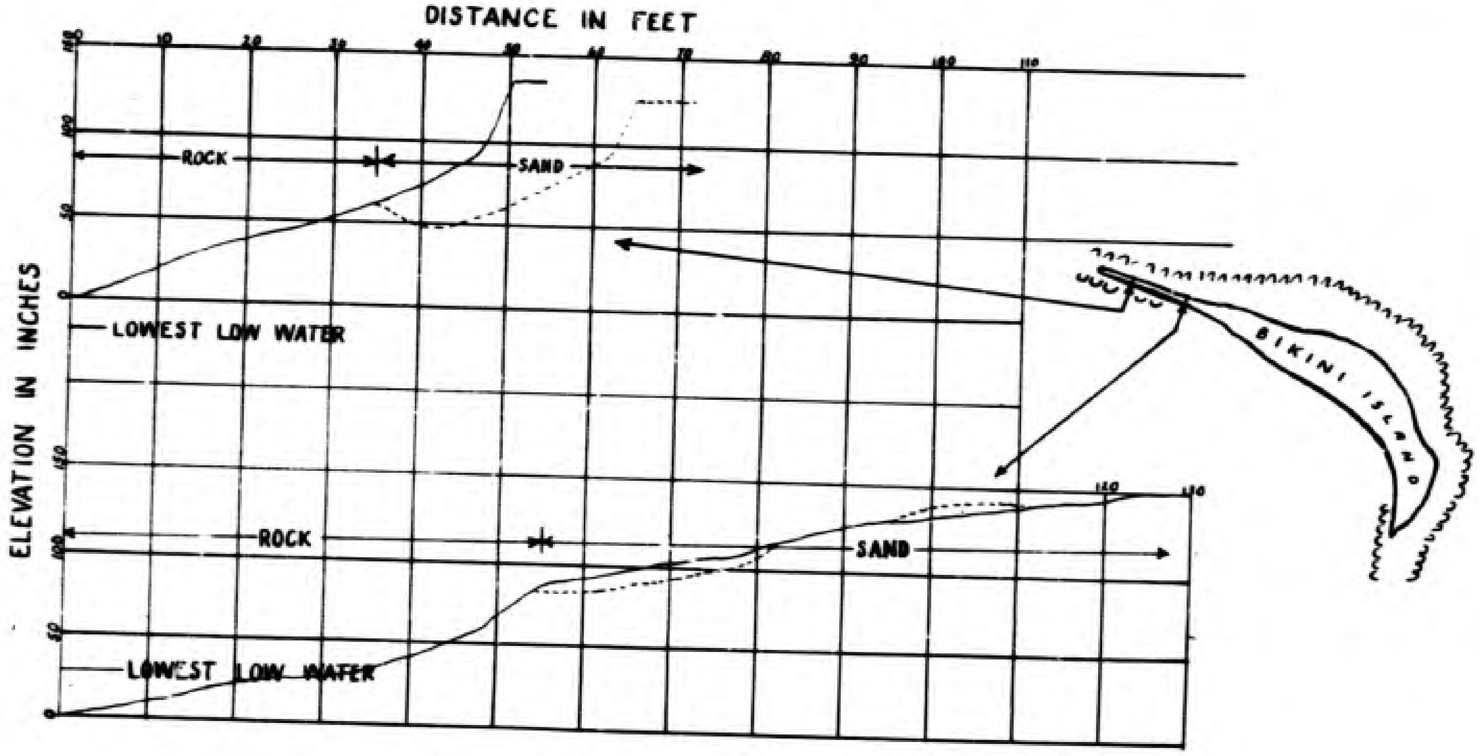
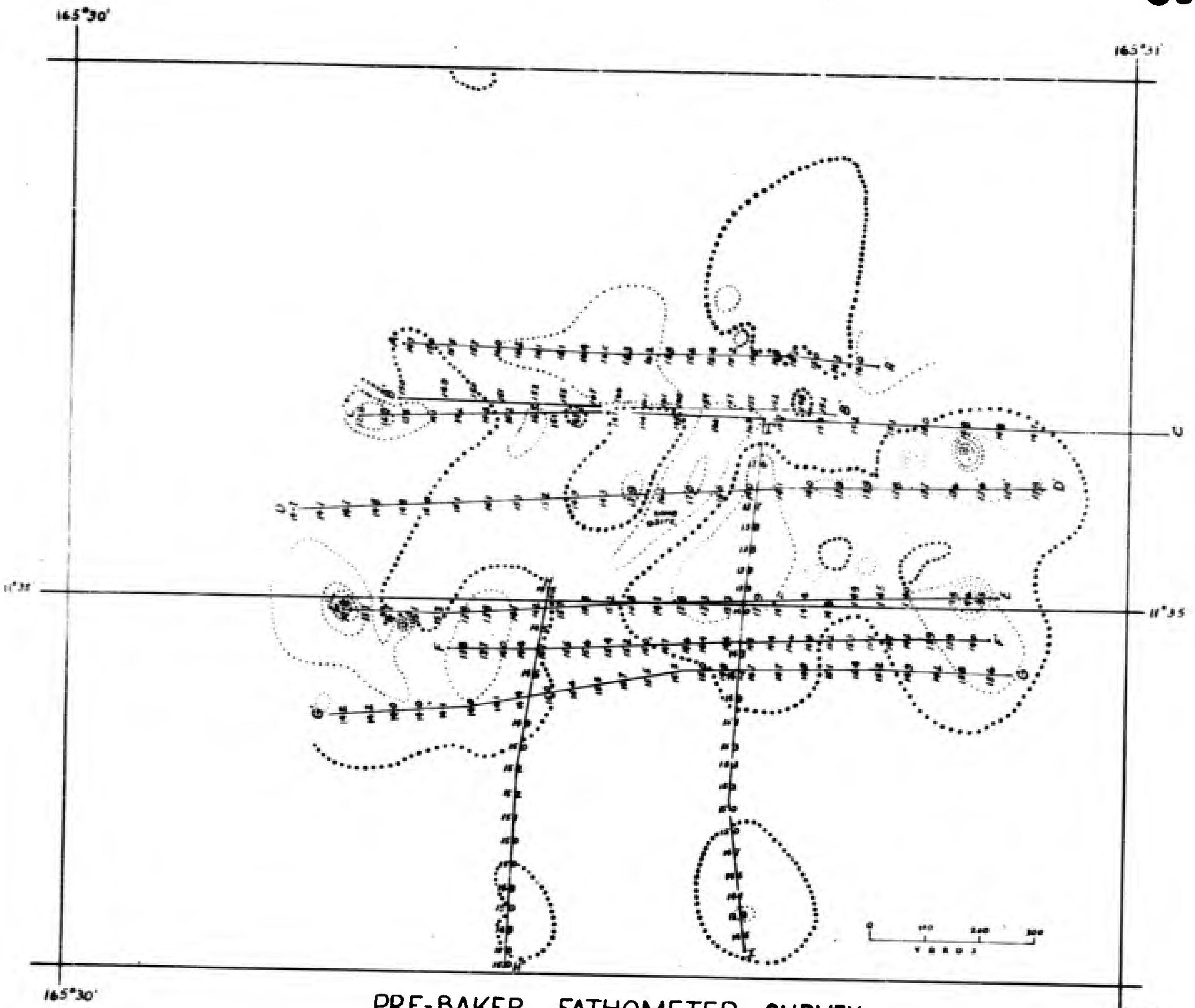


PROFILES OF LAGOON BEACHES

BEFORE BAKER DAY (July 6) ————
AFTER BAKER DAY (July 31) ---------

FIGURE 24



PRE-BAKER FATHOMETER SURVEY
DEPTH IN FEET CONTOUR INTERVAL-10'

FIGURE 25

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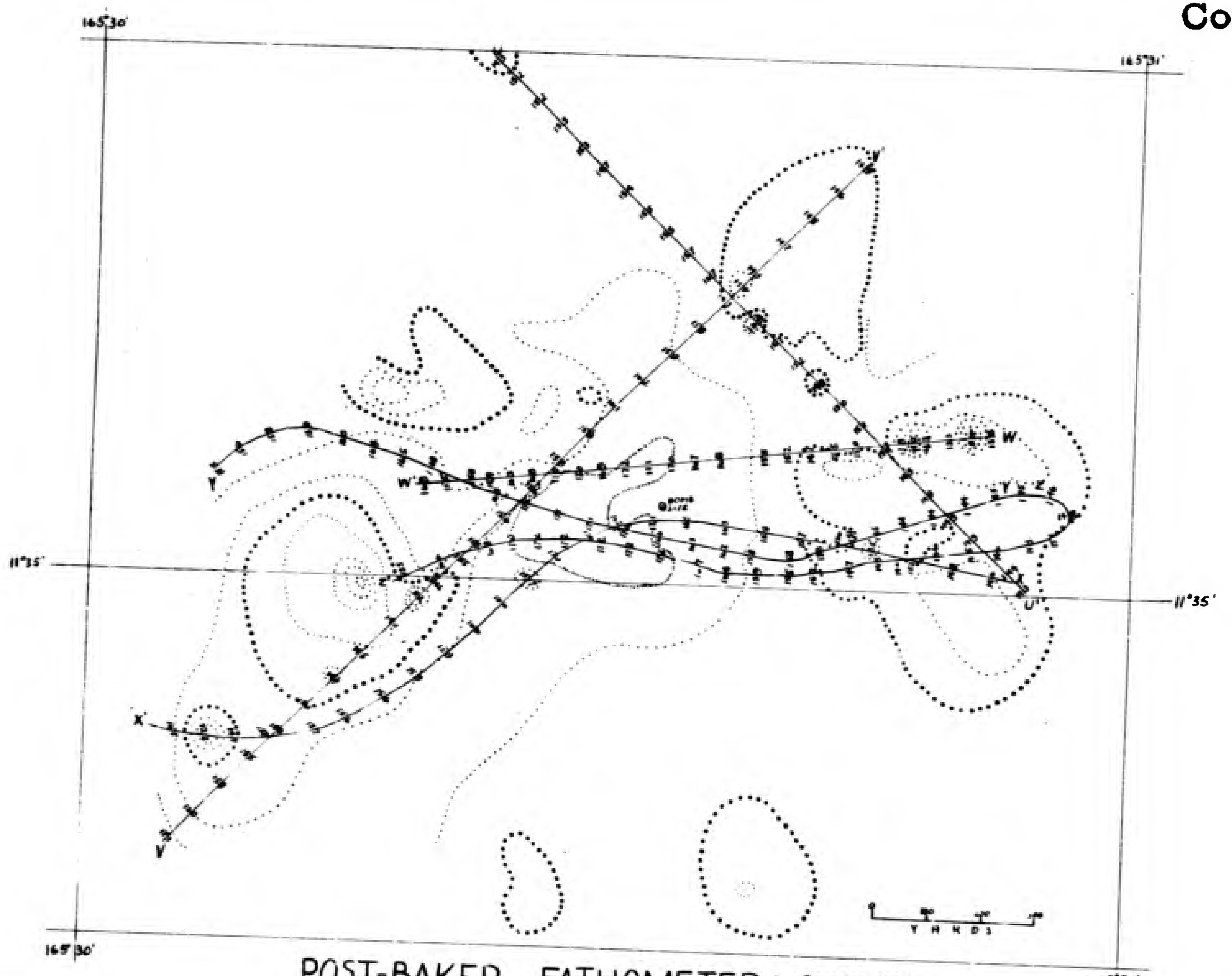
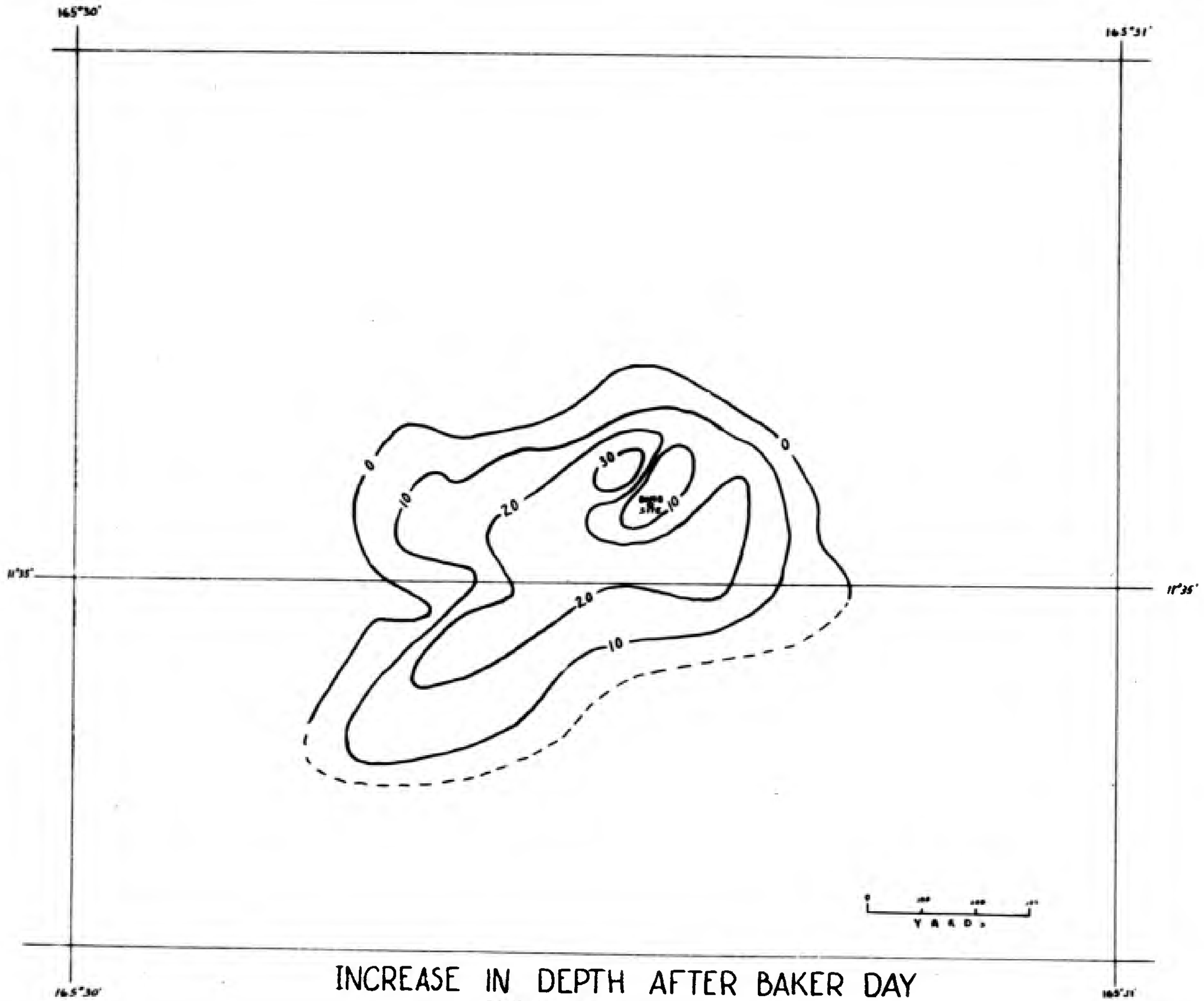


POST-BAKER FATHOMETER SURVEY
DEPTHS IN FEET CONTOUR INTERVAL 10'

FIGURE 26



INCREASE IN DEPTH AFTER BAKER DAY
CONTOURS IN FEET

FIGURE 27

As shown by Figure 25, the bottom in the central target area, like that in other areas of the lagoon, was fairly irregular although there were no very shallow reefs nearby. The actual bomb position was over a small trough about 15 ft deeper than the surrounding area. After B Day it was impossible to follow exactly the earlier fathometer lines so no direct comparison of depths can be made. However, the post-B Day soundings show the presence of a depression about 175 ft deep where previously there was no depression and the bottom was about 155 ft deep. This crater evidently was the result of the bomb explosion.

The difference in depth before and after B Day is shown more clearly by another chart, Figure 27, This chart was made by superimposing Figures 25 and 26 and subtracting the depth of the pre-B Day contours from that of the post-B Day contours at all points where the two sets of contours crossed. A few additional values were obtained at points where the two sets of fathometer lines happened to cross each other. The resulting chart shows that the bomb caused a measureable increase in depth over an area 600 by 1100 yd. The greatest apparent depth differance was 32 ft, but this represents only the removal of a small hill and not a hole 32 ft deep in a previously flat surface. (It is easily possible also that the hill was still present but not found by the post-B Day survey) Over an area of about 250 by 700 yd the bottom was more than 20 ft deeper after B Day, the maximum difference being about 25 ft. Note that the center of this area lies more than a hundred yards southwest of the bomb site.

The net volume of bottom material removed was estimated from the contours of Figure 27 to be about 2,200,000 yd^3, a volume equal to that contained in a cube 130 yd on a side. This volume represents only the net amount of bottom material removed from the bomb site, and not the total, or gross, amount of material originally placed in suspension or blasted out by the bomb. Much of the original material displaced by the bomb settled back into the crater, partially refilling it, while the remainder was carried by currents beyond the bomb area.

Divers working in the bomb area after B Day reported the presence of at least 6 minor craters having estimated diameters of 20 to 100 ft, and thus mostly too small to show well on fathometer tapes. Some of the craters have slightly raised rims, while other have no rims. Depths were estimated at 6 to 10 ft, and the bottom was thought to consist of mud. The origin of these craters is unknown but they were not present before B Day. It is possible that they are depressions caused by the impact of heavy machinery or ordnance, or possibly they are pits through which water trapped within the rapidly deposited sedimets escaped as the weight of overburden increased.

3. Bottom Sediments.

Before B Day, sediment samples collected at the bomb site consisted of coarse-grained algal debris mixed with less than about 10% sand and mud. The sand and mud probably resulted from the chemical or bacterial breakdown of the calcareous algal debris because vertical core samples exhibited higher percentages of mud and sand mixed with the older algal debris found near the bottom of the cores, than with the relatively freshly deposited algae at the top of cores. Neither sand nor mud, however, formed a layer separate from the algal debris. In this part of the lagoon, coral was found only on a few isolated shoal areas (coral heads). No significant amounts of coral occurred on the deeper flat bottom between these shoals.

Bottom samples taken after B Day near the explosion point were entirely different in character. Instead of algal debris, mud or sand was found, particularly in the area just west and north of the bomb site. The sediments were further explored by cores taken at intervals along an east-west line through the area. Cores beyond about half a mile from the bomb site consisted of algal debris covered by a thin layer of mud. In one core the mud overlay several stems of algae which were still green colored. Cores taken nearer the center of the bomb site showed a progressively thicker layer of mud which was separated from the lower algal debris by an intervening layer of sand. A core very near the bomb site contained 14 in. of mud overlying 22 in. of of fine to medium sand, and the core was too short to reach the algal debris below.

Divers working in the bomb area reported even greater thicknesses of mud. At one place 14 ft of "mud" (possibly mud and the underlying sand) were found. Divers also discovered that there was a layer of opaque and turbid water in the bomb crater which gradually became denser toward the bottom and graded into the bottom mud.

Preliminary examination of the sediments showed no evidence of crushing or breaking up of either coral or algae into fine-grained fragments by the force of the bomb. The layered distribution of sediments found after B Day does indicate, however, that the bomb set up turbulence which quickly eroded the bottom below the bomb and put all the sediments into suspension. When the turbulence decreased, the coarser algal debris settled out first, followed by the finer sand, and finally by mud. The mud settled so slowly that some of it was carried a mile or more from the bomb site before it was deposited, and some even remained in suspension two weeks after B Day.

The presence of a layer of mud and sand several feet thick indicates that a much greater thickness of the original sediment must have been disturbed, because of the relatively low original percentage of mud and sand mixed with the coarse algal debris. When the sediments have been more completely analyzed, perhaps an estimate of the total thickness of sediment disturbed can be made.

4. Radioactivity of Bottom Sediments.

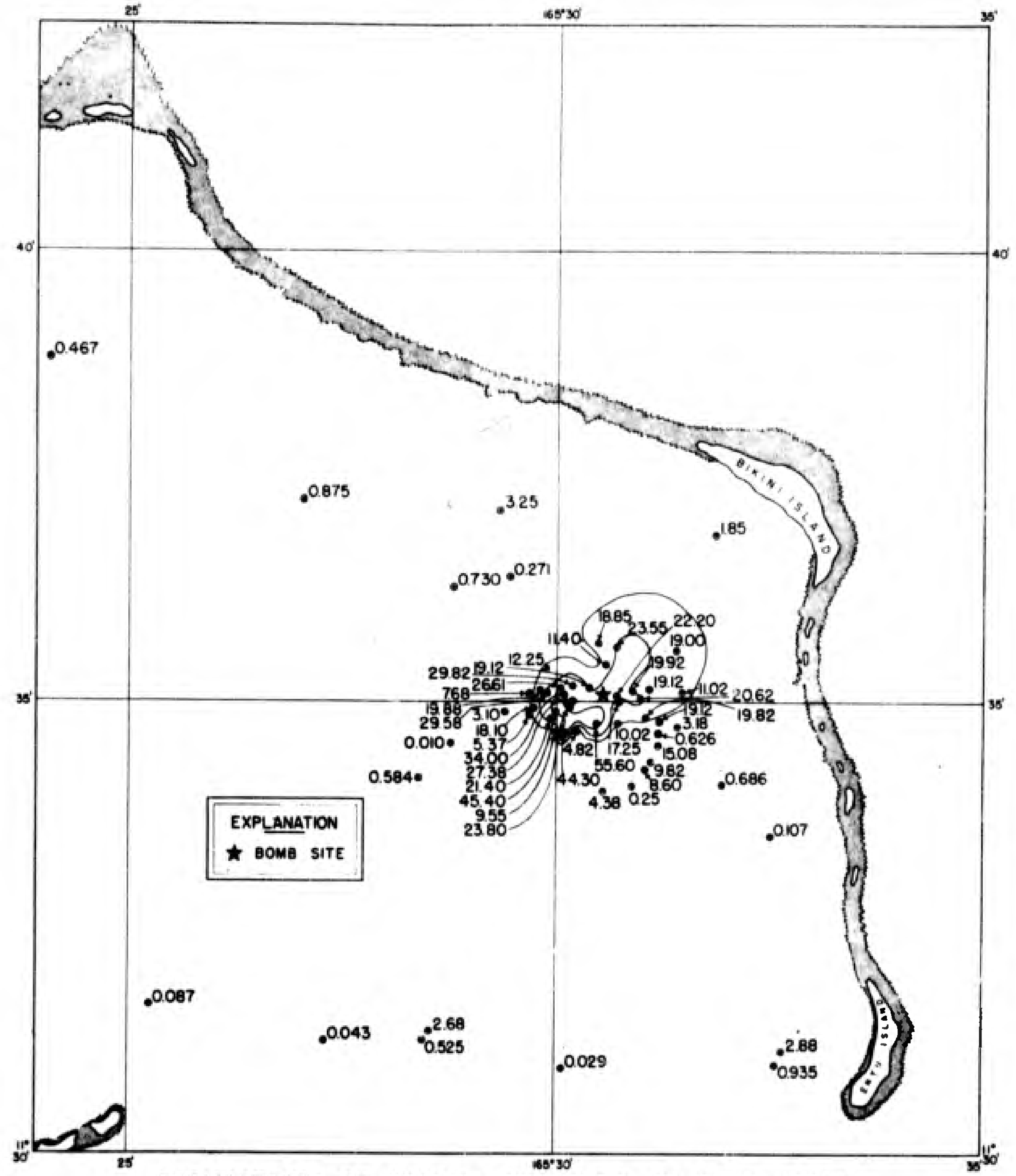
Bottom samples were collected from the bomb site for several days beginning with August 1, B Day plus 6 days. The radioactivity measurements for the samples obtained on August 1, 2, and 3 are plotted in Figure 28. Radioactivity is expressed in microcuries per gram of sediment, computed back to a time 4 hr after the explosion.

The highest radioactivity (40 to 50 mc/gm) was found in an area between one-half and one-quarter mile southwest of the bomb site, roughly coinciding with the area of greatest depth difference, Figure 27. Radioactivity decreased sharply outward from the zone of highest values, so that beyond about one mile from the bomb site there were very few samples having more than one mc/gm. It is notable that samples composed largely of mud showed the highest values. Morever, the layer of mud found in the upper parts of vertical sediments cores taken near the bomb site was very highly radioactive, whereas the coarser algal debris below the mud layer was only slightly radioactive.

The foregoing represents only a preliminary summary of the effect of the B Day atomic bomb on the floor of Bikini Lagoon. When more study is given to these data and when other data, not now available, are included, the charts and some of the conclusions may be changed.

5. Radioactivity of Beaches.

In the days immediately following Test B the intertidal zone and the beaches of many islands showed appreciable radioactivity. The beach on the lagoon side of Bikini was radioactive up to the high tide mark and on the spit northwest of Bikini Island instruments showed only a 5 hr tolerance at B Day plus 5 days. The field measurements showed that the upper part of the beach, and the sand washed inland beyond the beach, was inactive. The edge of the area of radioactive sand on the beach was very sharp. These facts indicate that, as would be expected, radioactivity was induced not by the waves which first struck the beach, but by radioactive water later brought into contact with the beach by currents from the bomb site.



RADIOACTIVITY OF BOTTOM SEDIMENTS OF BIKINI ATOLL
COMPUTED FOR BAKER PLUS FOUR HOURS
EXPRESSED IN MICROCURIES PER GRAM

FIGURE 28

BIOLOGICAL EFFECTS OF TEST BAKER

1. General:

Definite but comparatively minor biological changes occurred after Test B; the poverty of the flora and fauna of the lagoon and the inner reefs is undoubtedly one of the reasons for the absence of more significant ecological effects.

2. Biochemical and Bacterial Changes:

Following B Day there was marked decrease in the amount of dissolved oxygen and a corresponding increase in dissolved phosphate and in bacterial numbers in the bottom waters of the northeastern section of the lagoon. The area involved extended from the center of the target array north to the reef between Bikini and Amen Island and west from Bikini Island to a line through the center of Romuk Island. The lowest oxygen content, about 1.5 ml/L, was found approximately 4000 yd due west of the island of Bikini. The concentration of dissolved oxygen gradually increased westward and southward until the normal oxygen content, about 4.5 ml/L, was reached at the boundaries of the affected area. This value for the bottom waters, 4.5 ml/L, is slightly higher than the average for water near the surface; thus the photosynthetic activities of the bottom flora were not impaired outside the region of oxygen decrease. As the oxygen values diminished, the dissolved phosphate values increased, indicating oxidation of organic material and the accompanying liberation of biologically bound phosphate. At the same time the numbers of bacteria in the bottom water increased from about 10 cells per cubic centimeter prior to B Day to several thousands on B Day plus 10 days just west of the target center. Further west, several hundred bacteria per cubic centimeter were found in the bottom water while the surface water at all stations contained less than 50 per cubic centimeter. This vertical distribution of bacteria is a complete reversal of that found before B day.

These inter-related biochemical and bacterial changes would normally be expected to take place only if large numbers of living animals and plants had been suddenly killed. The stirring up of the bottom sediments in the target area may possibly have resulted in suspending enough organic matter and bacteria to account for the effects, but the extremely low organic matter content of the sediments makes this unlikely.

3. Marine Algae:

Destructive changes in the marine algal population were noted in several places but with one possible exception it is believed that the effects were due to pollution by oil from the sunken and damaged ships. The exceptional area was found on the seaward reef off the mid-point of Bikini Island. In this area the corals seemed healthy but the algal buttresses in the Lithothamnion ridge were distinctly whitened, the algae appearing dead or dying. The base of the whitened zone was covered by most waves at low tide. This area was examined on 18 Aug 46, the last day of observation on Bikini. It may represent a very localized condition as the reefs immediately to the north and south did not show such effects when examined on August 13 and 14. If the algae were killed by radioactivity the effects may become more widespread with the passage of time.

On the lagoon side of Amen the water was very murky and coral heads were fouled with a scummy growth of algae that certainly was not present when the area was examined in April. This growth covered the dead parts of all coral colonies, encroaching on but not covering the living parts. Both algae and coral showed marked radioactive contamination, but it is believed that the algal growth and the unhealthy condition of the corals was caused chiefly, if not entirely, by pollution.

On the southwest side of the atoll, along the margin of the reef on the sea side of Oruk Island, many of the sponge-type colonies of Lithothamnion had lost their pink and purplish color, appearing gray and lifeless. Some of these colonies and parts of the smooth algal pavement were covered with a growth of green algae (Enteromorpha). The algae were only mildly radioactive and it is believed that the widespread changes of the reef margin were caused mainly by oil contamination - oil being present in large amounts. This belief was confirmed by the good condition and healthy purplish color of Lithothamnion colonies in shallow water below low tide level where they would be unaffected by floating oil.

In many places where the reefs were re-examined no appreciable changes of any kind could be noted - even in areas where the reef organisms showed a relatively high radioactive count, and in others where large amounts of oil were present. Some specimens of Halimeda and soft green algae dredged from between the target ships had only a 30 min tolerance, yet they appeared fresh and healthy. It does not follow, however, that these reef and lagoon organisms have escaped without damage. Their ability to absorb radioactivity and survive is remarkable, but conceivably destructive effects may have been only deferred.

The important role of algae as a primary concentrator of radioactive material from sea water, through photosynthesis of organic compounds and the accompanying extraction of elements present in very dilute concentrations, should be emphasized. Many marine invertibrates and certain fishes are algal feeders, and the concentration of radioactivity by algae thus starts a food chain which eventually effects the larger carniverous fishes, including most food and game fishes, that prey upon the plant feeders. In cooperation with the Radiological Safety Section an extensive investigation was conducted after B Day to determine the geographical distribution of radioactive contamination of the algae and the effectiveness of different types in concentrating radioactivity. Table II gives data on counts obtained per unit weight from specimens of different genera collected in areas of high and low contamination. In general, the intensity of radioactivity in living algae was much greater than that in the sand or other inorganic sub-stratum to which they were attached.

It is evident that the algae in regions of highest contamination accumulated much more radioactive material per unit weight than those in areas of low concentration. Halimeda and other genera living on the lagoon floor were specially heavily contaminated. Within the groups of Chlorophyceae and Myxophyceae the variation in radioactivity within a single genus such as Caulerpa or Neomeris even in the area of heavy contamination, was much greater than the variation between genera. There is no consistent difference under given conditions between calcareous and non-calcareous forms.

4. Land Plants:

Locally on the lagoon side of Bikini Island salt water from the waves caused by the explosion flowed inland killing some vegetation, especially grasses and the Tacca Plant. No other damage of consequence to land plants was observed.

5. Marine Invertebrates:

Within the target area, listening tests using a C-23 hydrophone and a portable amplifier showed that the noise of snapping shrimp, one of the most characteristic underwater noises in the tropics, was silenced after Test B, probably because of the destruction of these animals by the underwater shock. Beyond 2000 yards the intensity of shrimp noise appeared unaffected.

All other damage to marine invertebrates appears to have been due to pollution by oil which escaped from sunken and damaged target ships and in many places literally soaked the beach sand or covered large areas of the exposed reef flats. The invertebrate animals injured or killed by these oily accumulations will not fully recover or possibly even reappear in these spots until the oil and tarry residues are gone or are covered by new beach deposits.

Corals were among the animals most seriously affected by pollution. Midway between Bikini and Amen Islands, for example, a rich growth of coral has been extensively damaged. The upper part of each colony - the part lying above extreme low water, has been killed and is now white and clean though the remainder which is always below water is alive and apparently healthy. When this area was examined on August 16th, films of oil were still abundant at low tide level, the bottom of the damaged zone. On the sea reef of Amen Island white dead patches appeared on the crowns of globular coral colonies probably as a result of oil slicks passing over the reef. Other colonies showed abnormal colorations, the bright green center of the corallites giving signs of disintegration with the intervening ridges being whitened.

TABLE II
RADIOACTIVITY AND LOCATION OF ALGAL SPECIMENS

a. From highly contaminated area

Genus	Group	Location	Count Per 10 mg	Date Collected
Laurencia	Rh	1D	6290	8/4
Laurencia	Rh	1D	448	8/5
Laurencia	Rh	1D	708	8/5
Centroceras	Rh	1D	270	8/5
Centroceras	Rh	1D	566	8/6
Liagora	Rh	3D	1380	8/4
Jania	Rh	1D	1346	8/6
Halimeda	Cl	1D	2764	8/4
Halimeda	Cl	1S	2054	8/4
Halimeda	Cl	4D	5286	8/7
Halimeda	Cl	4D	6900	8/7
Halimeda	Cl	4D	4100	8/7
Halimeda	Cl	4D	5736	8/7
Halimeda	Cl	4D	3920	8/7
Halimeda	Cl	4D	4651	8/7
Neomeris	Cl	1S	16300	8/4
Neomeris	Cl	2D	708	8/5
Caulerpa	Cl	2S	3820	8/4
Caulerpa	Cl	1D	1230	8/5
Caulerpa	Cl	1D	485	8/6
Caulerpa	Cl	4D	11070	8/7
Caulerpa	Cl	4D	29400	8/7
Microdictyon	Cl	1D	1540	8/6
Microdictyon	Cl	4D	24200	8/7
Microdictyon	Cl	4D	6700	8/7
Microdictyon	Cl	4D	12600	8/7
Cladophora	Cl	3S	9750	8/4
Udotea	Cl	4D	21000	8/7
Udotea	Cl	4D	18800	8/7
Enteromorpha	Cl	0S	338	8/8
Turbinaria	Ph	1S	755	8/5
Pocockiella	Ph	1D	760	8/5
Pocockiella	Ph	4D	7200	8/7
Myxophyceae	My	1S	7950	8/4
Myxophyceae	My	0S	1140	8/8
Myxophyceae	My	0S	1201	8/8
Lyngbya	My	4D	12100	8/7
Lyngbya	My	4D	11100	8/7
Dichothrix	My	0S	550	8/5

b. From slightly contaminated area distant from target or on protected part of reef.

Genus	Group	Location	Count	Date Collected
Halimeda	Cl	OS	839	8/6
Halimeda	Cl	1S	10	8/9
Caulerpa	Cl	2D	6	8/4
Caulerpa	Cl	1S	6	8/4
Caulerpa	Cl	OS	884	8/6
Caulerpa	Cl	2D	125	8/9
Neomeris	Cl	1S	12	8/4
Neomoris	Cl	2S	36	8/4
Neomoris	Cl	2D	466	8/9
Microdictyon	Cl	1S	11	8/4
Microdictyon	Cl	1S	12	8/9
Enteromorpha	Cl	OS	33	8/8
Dictyosphaeria	Cl	2S	18	8/4
Lithothamnion	Cl	1S	17	8/9
Cladophora	Cl	1S	163	8/9
Myxophyceae	My	OS	1452	8/6
Myxophyceae	My	1S	19	8/9
Myxophyceae	My	1S	24	8/9
Myxophyceae	My	1S	16	8/9
Myxophyceae	My	1S	603	8/9
Schizothrix	My	1S	28	8/6
Schizothrix	My	OS	15	8/9
Schizothrix	My	OS	60	8/9
Dichothrix	My	OS	18	8/9
Lyngbya	My	1S	503	8/6

Algal Groups

Rh - Rhodophyceae
Cl - Chlorophyceae
Ph - Phaeophyceae
My - Myxophyceae

Location

0 - Intertidal
1 - Near Shore
2 - Halfway out on reef flat
3 - Near outer reef margin
4.- On Lagoon bottom
S - Shallow
D - More than 1" deep

Snails and clams dredged from the bottom in the target area on B Day plus 13 days were apparently completely normal, although radioactivity of the bottom material was still far above the level declared safe for human tolerance. Other localities inshore towards Bikini Island likewise showed no immediate damage to bottom animals.

Preliminary examination of net hauls from 23 positions in or immediately outside of Bikini Lagoon showed no marked injury to the population of small free swimming or floating invertebrates (plankton). Larval and other characteristic lagoon forms were still evident, although there appeared to be some reduction in the amount of plankton present at certain positions in the lagoon. Many plankton hauls showed a much higher level of radioactivity than the surrounding water indicating that these small organisms may concentrate radioactive materials, possibly through ingestion of radioactive plants. In the target area the plankton nets were fouled by oil during each tow and this may have been the source of the apparent radioactive contamination of the plankton.

6. Reef Fishes:

Post B Day investigations during August disclosed no significant reduction or change in the relative abundance of reef fishes at Bikini Atoll as a result of the atom bomb explosions. The average index of relative abundance (that is the average number of fish per square yard recovered from an area effectively poisoned with rotenone) for 22 northern Marshall Island stations poisoned prior to A Day was 0.12 for ocean reefs and 0.13 for lagoon reefs. After B Day the index for 6 ocean reef stations at Bikini was 0.14 and for one lagoon reef 0.13. The fluctuation in the value of the index among the various stations was about what would be expected in the sampling of such fish populations.

Although there was no immediate change in abundance, many reef fishes collected after B Day were radioactive and at least in some areas the amount of radioactivity appeared to increase with the passage of time. Detectable damage to the reef fish population may occur over a period of several months or years either through direct lethal effects or through injury to reproductive processes.

7. Pelagic Fishes:

At Bikini during post-B Day period of 31 July to 17 August the combined catch of pelagic and semipelagic fish per line hour declined to 0.077, or 48% as compared to the value of 0.148 in the previous fishing period from 4 to 17 July. The proportion of the various species taken by trolling altered radically after B Day, there being an increase in percentage, 12.2 to 48.6%, and also in absolute count, of the catch of yellowfin tuna and oceanic skipjack. Both of these species are considered purely pelagic, The sharp decline in total catch resulted from a reduced take of two species, the dogtooth tuna and the black skipjack. These latter species are considered semipelagic, being frequently taken in the lagoon, and in the lagoon passes. The black skipjack occur also in occasional schools outside the atoll. Dogtooth tuna had previously been the predominant fish of the catch. It is possible that the decline may have been simply a reflection of a general contemporary trend occurring over a wide area and in no way connected with the bomb. The following figures suggest such a trend:

Proportion of Dogtooth Tuna in Troll Catch

Dates	Area	Per Cent
4 to 17 July	Bikini	52.5
18 to 30 July	Rongerik-Rongelap	30.5
31 July to 17 August	Bikini	18.4

A less marked decline in the catch of the various species of bottom and lagoon fish occurred concurrently with the decline in the semipelagic species. Many of the fish tested, especially damsel fish, family Pomacentridae, proved to be radioactive. As with reef fishes it is expected that subsequent sampling will be required to rigorously assess the bomb damage.

8. Land Animals:

The Birds of the atoll re-examined on Bikini and other representative islands after B Day were all apparently unharmed except for minor effects of floating oil.

Land snails living under slabs of beach conglomerate near the high tide line on the lagoon side of Bikini Island were completely normal in appearance and behavior on B Day plus 13, even though the beach environment was still radioactive.

SEISMIC EFFECTS ON BIKINI ATOLL FROM TEST BAKER

1. Ground Movement

Measurements of seismic effects from the underwater explosion on the islands of Bikini Atoll were made by groups of the Oceanographic section. Seismic measurements on other Pacific islands and in the continental United States were under the cognizance of the Remote Measurements Section. On the atoll itself, records of ground movement produced by the explosion were obtained on Amen, Yuro and Bikini Islands.

The recorded periods and accelerations of the seismic waves at these stations were as follows:

			Accelerations	
Location	Periods in Seconds	Vertical	Longitudinal	Transverse
Bikini	0.03 to 0.25			
Amen	0.20 to 0.85	25 cm/sec^2	41 cm/sec^2	42 cm/sec^2
Yuro	0.10 to 0.33	10 cm/sec^2	10 cm/sec^2	4 cm/sec^2

The measured accelerations correspond to an earthquake of magnitude between 5 and 6 on the Rossi-Forel Scale. The difference in the observed period at Amen compared to the other two stations is believed to be due to differences in the instruments used. No single instrument will record the entire range. At Amen there were also recorded transverse and surface waves ranging in period from 1.8 seconds to 3.7 seconds.

Maximum displacements observed were:

		Components	
Location	Vertical	Longitudinal	Transverse
Amen	1.25 mm.	1.75 mm.	1.3 mm.
Yuro	0.50 mm.	.50 mm.	0.1 mm.

Since Yuro is on 25% farther from the blast than Amen these values should be more nearly equal. However, the instruments on Amen were placed on a concrete foundation while the ones on Yuro were on sand. This may account for the discrepancy in the values of the displacement. Displacements and accelerations could not be determined at Bikini because high amplitudes put the peaks off the recording paper.

The movements of the earth particle at the two stations were nearly identical, the initial motion being up and away from the blast. The later motion was complicated but characteristic of movement due to explosions.

The Amen record indicates two surface waves arriving while no such indication appears on the Yuro record. This will be studied more closely in the near future.

2. Identifying Characteristics of Seismic Signals from Explosions.

The tremors produced by the bomb were recorded at seven stations on the mainland at distances of approximately 5000 mi. These records have been studied by personnel of the Coast and Geodetic Survey in comparison with earthquake records, to see if some characteristic could be found that could be used to identify explosions of atomic bombs. It was noted that after an explosion the initial motion of the ground at the seismic station is always away from the explosion whereas in an earthquake the initial motion may be either away from or toward the epicenter. If a string of stations were placed around a suspected area and all recorded on initial motion away from the source it would indicate the probability but not certainty that a large explosion had occurred. If, however, any of the stations showed a movement in the opposite direction and earthquake would be indicated. If such a string of stations were to be set up, two and preferably three of them should be tripartite stations. These stations would show the direction from which the tremors came. Thus, two or more such stations would give the location of the source of the tremors.

At locations nearer the explosion point, the ratio of amplitudes of the compressional to the transverse waves is apparently much greater for an explosion than for an earthquake.

CONFIDENTIAL

ENCLOSURE G

"Summary Report on Electromagnetic Propogation"

by

Dr. E.W. Thatcher

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Summary Report on Electromagnetic Propagation

I. Abstract:

During the Atomic Bomb Tests at Bikini, experiments were planned to determine the effects of the detonation on radio waves. Chief among these were (1) the attenuation resulting from propagation through the cloud (2) the radar reflective properties of the cloud and (3) the atmospheres electrical disturbances developed by the explosion.

Conclusions are (1) short range (less than 50 mi) propagation suffered attentuation only if the line of propagation passed directly through the region of the cloud burst. Long range propagation showed no change in characteristics attributable to the bomb. (2) Weak radar echoes were observed briefly on X band from the air burst. Strong echoes were obtained on S, X and K band from the column thrown up by the underwater burst resulting in temporary obscuration of targets beyond the cloud. (3) Atmospheric noise was reported on only one receiver operating at maximum sensitivity approximately 16 mi from the air burst.

II. Introduction.

Electronics devices were extensively used in the Tests. Many such instruments served as effective means for detecting, transmitting or recording physical phenomena connected with the detonation (e.g. pressure radioactivity, etc.). Another large group was used for the direct determination of electromagnetic effects, such as the influence of the explosion on the radio waves, the radar reflective properties of the bomb cloud and the atmospheric electrical disturbances developed by the explosion. It is with the second of these functions that this summary report is concerned.

The organization and general plan of the electronics instrumentation program have been outlined in Annex G of the JTF-1 Operation Plan (Enclosure N hereto). The planning, execution, and report, the major part of the program, was carried out by two groups, an Army Air Forces Group headed by Col. D. F. Henry (013L) and the Bureau of Ships Electronics Co-ordinating Office headed by Capt. C. L. Engleman (013D). The latter group was aided substantially by the contribution of civilian personnel supplied by the Naval Research Laboratory and by the Signal Corps. Some observations also were made at distant points under the supervision of the remote Measurements Group (013J) headed by Cdr. G. Vaux in the Office of Naval Research.

Among the principal objectives of electromagnetic propagation tests, the following questions suggest themselves:

1. Does the nuclear fission explosion affect radio propagation at the instant of explosion?
2. At what distance from the burst point are effects, if any observed?
3. Does the subsequent cloud formation influence radio propagation? Is this influence felt only on transmission directly through the cloud?
4. In what frequency bands are effects attributable to the bomb observed?
5. What is the nature and duration of any change observed?

6. What electromagnetic disturbances are generated by the detonation itself?
7. What are the radar reflective properties of the Atomic Bomb cloud?

It should be pointed out that a monitored radio or radar signal may show changes in observable characteristics due either to changes in propagation or to changes in the equipment or its orientation. It is not always possible to distinguish clearly between these causes though the time of occurrence of any marked change may be used with considerable confidence in correlating observed results with their immediate causes.

III. Instruments and Equipment.

A. Ship Installations.

Radio and Radar Installations used for propagation tests on target vessels, included 18 channels covering a range of frequencies from 7 to 10,000 megacycles. Table (1) summarizes the characteristics of the transmitting equipments used. Signals were monitored aboard the AVERY ISLAND with appropriate receiving stations each of which consisted basically of the following components: Antenna, transmission line, receiver, graphical recorder, camera, panoramic adaptor, and pulse analyzer.

B. Land Installations.

Seven radar installations were made on Amen Island. Two were S band equipments, three were X band and two were K band. Description of these radar sets as well as the receivers on the AVERY ISLAND used to monitor the transmissions as included in the report on Project IV-2 of 013 D.

On Kwajalein five SCR 299 transmitters were keyed to transmit a continuous tone modulated signal on 4960, 5880, 7010, 8845, and 11,205 kilocycles respectively. These signals were monitored at Eniwetok and also in the AAF aircraft serving as drone control ships in the immediate vicinity of Bikini Atoll.

Signals were monitored at many more remote stations during the period of the tests. Results have been reported in IV-14, IV-15 and VIII-16. Since in no case was any effect attributable to the bomb detonation observed, details of these installations are not presented in this summary.

C. Airborne Equipment.

AAF Mother aircraft were equipped to provide propagation search of all frequencies between 0.5 and 4000 megacycles. Receivers were equipped with AN/APA-23 tape recorders and AN/ANQ-1A wire recorders. In addition the operator monitored all audible signals and recorded any unusual circumstance which might aid in interperating the records obtained.

In each of the four drone aircraft was mounted an APT-5 jamming transmitter pre-tune in the 1000 megacycle region and one SCR-522 VHF transmitter which, in addition to carrying audio pulse from Geiger counters simultaneously transmitted a 1000 cycle tone for propagation studies. These transmitters ranged in frequency from 136.90 mc to 137.34 mc.

The group of F-13 photographic aircraft were equipped with AN/APQ-13 radar bombing systems. This is an X band radar with PPI presentations and was used to indicate whether radar reflections from the cloud could be detected from the air. Each of these aircraft also carried a SCR-718 altimeter which was observed visually before, during, and after the time of detonation.

IV. Results.

Consideration is here given first to what might be called definite negative results. Their importance lies in delimiting circumstances in which neither the bomb nor its after effects result in any observable change in propagation.

1. adio transmitters left in operation on three of the target ships were monitored at Naval radio installations throughout the Pacific area and in continental U. S. Results, while not entirely conclusive, show no changes in propagation characteristics which can be attributed to the explosion of either bomb. Similarly Federal Communications monitoring stations in the U. S. and Alaska recorded emissions of vessels in the Bikini area. No effects attributable to the explosion were observed at any station.

2. Pulse modulated signals were transmitted from the JAMES F. KEYS to the US Naval Supplementary Radio Station at Guam and from the Naval Radio Station at Totsuka, Japan to the USN Supplementary Radio Station at Vaitogi, Samoa. These stations were selected so that the transmissions would pass over the Bikini area and due to multipath pheno-

mena would likely experience reflections both to the ionosphere and at the surface in the proximity of Bikini. The Bomb A explosion caused no effects on the radio signals passing along either of these paths. Observations by this activity were not made in connection with Bomb B.

3. X band radar transmissions from the PARCHE 1360 yd from the burst and PENNSYLVANIA 1740 yd distant were received on the AVERY ISLAND without change throughout the entire period embracing the Bomb A burst. In each case the line of propagation did not pass through the burst point or the cloud.

4. Radar transmission from Amen Island on S, X and K band were monitored on the AVERY ISLAND. Because of the late change in sector Axis this ship was forced to approach the arriving point on a course of 303° instead of 321° as originally planned. The line of propagation thus passed approximately 2800 yd from the NEVADA at its nearest Point. From the actual burst point the line was 3280 yd distant. It is significant that no attenuation or other change in signal characteristics were recorded in this transmission.

5. Attempts were made to detect the Bomb A cloud column by long range reflection from Hawaii on 56 kc. Special receiving equipment was installed to record any echoes above ambient noise level. No echoes were observed.

6. Radar detection was also attempted from Kwajalein 215 mi away by radar on 1200 mc. Although the radar followed a B-29 at 30,000 ft altitude to 190 mi no echoes from the cloud over the explosion were observed.

TABLE I

Target Ship Installations

CHANNEL	SHIP	EQUIPMENT	TYPE	FREQUENCY (MC)	POWER PEAK	(KW) AVG.	PRF CPS	PULSE LENGTH M/sec	ANTENNA BEAM-WIDTH	RPM
1	PARCHE	ST	Search (Sub)	10,000	30	.03	1500	0.3	30.0° h* 10.0° v**	8
2	PENNSYLVANIA	Mk 8 Mod.3	Fire Control	9,000	30	.014	1800	0.3	.9° h 3.5° v	Scans 10 cps
3	PENSACOLA	SP	Fighter Director	2,800	700	.42	600	1.0	2.7° h 2.7° v	6
4	PENSACOLA	SG-a	Search	3,000	50	.08	800	2.0	15.0° v 5.6° h	8
5	PENSACOLA	Mk-28	Fire Control	3,000	30	.018	1800	0.5	6.5° h 6.5° v	Scans 30 cps
6	WAINWRIGHT	SG-a	Search	3,000	50	.08	800	2.0	5.6° h 15.0° v	8
7	PARCHE	SV-3	Search (Sub)	3,500	300	.2	300	1.0	5.5° h 60.0° v	6
8	WAINWRIGHT	SC-3	Search	220	200	.06	60	5.0	20.0° h 60.0° v	4
9	TALBOT	SC-3	Search	192	200	.06	60	5.0	20.0° h 60.0° v	4
10	WAINWRIGHT	BN	Interrogator	180	1.5	.015	400	7.0	Vert. Dipole	
11	TALBOT	BN	Interrogator	170	1.5	.015	400	7.0	Vert. Dipole	
12	PARCHE	BN	Interrogator	160	1.5	.015	400	7.0	Vert. Dipole	
13	PENNSYLVANIA	TBL	Comm.	7,655		.2			Whip Antenna	
14	PENSACOLA	TBK-5	Comm.	11,410		.2			Whip Antenna	
15	PARCHE	TBL	Comm.	15,715		.2			Whip Antenna	

* h - horizontal

** v - vertical

7. At 18 mi. 200 megacycles shipborne radar failed to detect the ionized column.

8. S band radar (3300 mc) located on Amen Island produced an excellent record on which no cloud reflections appear. X band radar showed only a brief echo at the instant of burst.

9. A number of changes in frequency, amplitude or pulse repetition rate of radio emissions accompanied the mechanical shock applied to equipment by the blast. These included signals from the target vessels PARCHE, PENNSYLVANIA and TALBOT and one of the airborne television equipments. It is most unlikely that further study of these records will throw any light on the propagation problem.

10. In certain other cases, notably the S band signals from the PENSACOLA and one of the X band channels jamming from unidentified sources has prevented analysis and interpretation of the records.

The scope of the effect of the explosions on propagation is indicated by the limited number of cases in which changes occurred at the instant of detonation and persisted for varying lengths of time thereafter. These have been summarized in the following table. (Table 2)

V. Comments on Difficulties Experienced.

Plans for repeating propagation tests from target vessels in Test B were cancelled because of possibility of interference with the bomb firing or de-energizing circuits.

Signals on channel #4 and #5 both in the S band were not received because the change in sector axis forced the AVERY ISLAND out of the transmission path at the time of the air explosion. Channel #3 on 2800 megacycles was masked by excessive interference.

The timing signal error in Test A and failure of timing boxes resulted primarily in the loss of photographic records. Two continuous film cameras on AVERY ISLAND were started by the "-5 sec" signal which was transmitted more than 6 sec. after detonation. On Amen Island 2 cameras on the MPG 1 radar remained inert when timing boxes did not operate.

Some photographic data also was incomplete due to mechanical camera failure after starting on Test B. Both MPG console B and the APG-7 Fairchild jammed after approximately 1/3 of their maximum run.

Table 2 (A)

ABLE TEST

TYPE AND FREQUENCY	LOCATION TRANSMITTER	LOCATION RECEIVER	REMARKS
SG S Band	WAINWRIGHT DD419	AVERY ISLAND AG-76	Dropped 20 db at blast normal after 8.7 sec.
SC-3 P band, 220 mc	" "	" "	Dropped 11 db at blast normal 6 sec strong interference
BN FF 180 mc	" "	" "	Dropped 6.5 db at blast normal at 7.3 sec.
TBK - 5 11.4	PENSACOLA	AVERY ISLAND	No signal received after 0410 noise level up 13 to 18 db 5.5 sec after M for 120 sec.
APQ-7 X Band #1 9374 mc #2 9388 mc	Amen Island		New echo near point of burst. Cloud attenuates echoes from ships behind for period of 6 sec.
AN/APQ-13 X Band	F-13 Photographic Aircraft	Same A/C	Detected shock wave to distance between 1 and 2 mi from point of burst
1400 mc	Unknown	"Mother Aircraft"	Logged at M-30 minutes and received until Mike Hour "cut out" at detonation and reappeared at M plus 8 min.
1500 mc	"	"	Same as above
APT SA 1000 mc	Drone III	Mother A/C III	Reduced in strength at Mike Hour. Returned to normal at Mike plus 8 min.

Table 2 (B)
BAKER TEST

TYPE FREQUENCY	LOCATION TRANSMITTER	LOCATION RECEIVER	REMARKS
AN/APS-2F S band 3300 mc	Amen Island	AVERY ISLAND AG-76	Drop of 10 db in 1 way transmission thru blast. Returned to normal in 45 sec.
AN/MPG-4 X band 9489	"	"	Drop of 10 db - in first 2 sec. Reflection of column covers entire fields (2600 yd wide) From 15-26 sec signal remained an average of 13 db below normal at 43 sec it had risen to 3 db below normal but fill again to 27 db below at 66 sec. Returned to normal at 4.5 min.
AN/APS-34 K band 23,800	"	"	Attenuation of unknown amount (Signals dissappeared) #1 reappeared at 335 sec, normal at 440 sec. #2 reappeared at 250 sec - normal at 400 sec.
AN/APQ-13 X band	F-13 photographic		Echo from cloud readily detected 7 to 10 min after detonation. Blacked out definitions of ships in central portion of target array.

VI CONCLUSIONS

Consideration of the location of receiving and transmitting points in the instances enumerated (Tables 2A and 2B) leads to the conclusion that not only were observable effects limited to the immediate vicinity of the detonations, but that marked attenuation resulted only when the propagation path lay directly through the position of the bomb and subsequent cloud formation.

Extensive coverage of the frequency range from .55 to 23,800 megacycles along <u>other</u> paths failed to reveal any propagation anomaly attributable to the atomic bomb. Likewise records of land, sea, and aircraft stations other than those within 25 mi of the detonation failed in all cases to detect any effects from the bomb.

From reports compiled to date the following additional specific conclusions can be drawn:

Test A

The Bomb A cloud returned no echo in the S band. The existence of an echo in X band is doubtful. Data on K band is lacking.

The airblast wave could be detected by airborne X band radar for 15 sec.

Marked attentuation was caused by the cloud in both X and K bands as shown by weakening of echoes from targets behind the cloud.

It is significant that in the case of one way transmission, except for the 1000 megacycle signal from Drone III and the two unidentified signals on 1400 and 1500 megacycles*, attentuation lasted for a maximum of 8.7 sec. X band echoes were obscured by the cloud for a similar period.

In only one instance were electromagnetic disturbances attributable to the Bomb A detonation observed. This was on the 11.4 megacycle channel which was tuned to receive the TBK transmission from the PENSACOLA. As a consequence of change in the sector axis on A Day the signal was not received and the receiver therefore operated at maximum sensitivity. Random noise was observed beginning about 5.5 sec after the blast and lasting some 2 min. The intensity during this period ranged from 13 to 18 db above normal background. The monitoring station was roughly 15 mi from the explosion.

Search of the electromagnetic spectrum from .55 to 4000 megacycles by AAF aircraft and at all participating land stations failed to detect any similar disturbance.

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* Attention is drawn to the circumstances that all 3 of these signals returned to normal strength at the same time (i.e. Mike Hour plus 8 min) also at this instant the drone II transmission on 7050 megacycles was also first received hour (C.F. report IV-10). This strongly suggests that some change in receiver characteristics at Mike Hour plus 8 min may be responsible for the changes observed. Further investigation is being made on these points.

Test B

The water column produced by the underwater explosion was readily detectable by air or surface radar.

The air blast wave could be observed on airborne X band radar for 7 sec.

Evidence indicated that the residual cloud was readily detectable by X band or higher frequency radar for a period of 5 to 14 min. For from 4 to 7 min the echo from the cloud was of sufficient intensity to obscure targets lying beyond the cloud.

Attentuation of 10 db or more was measured on S and K bands, in one way propagation while the K band signals from Amen Island disappeared entirely.

No noise or electromagnetic disturbance of any character was noted in connection with the underwater detonation.

APPENDIX - Projects on Electromagnetic Propagation

Number	Title	Reporting	Section
IV-2	Effects of an Atomic Explosion on the Transmission and Reflection of Electromagnetic Waves at Super High Frequencies	R. C. Giles	013D
IV-4	Observations of Radio and Radar Transmissions from Target Vessels during an Atomic Explosion	David Williams	013D
IV-7	Sferics Direction Finders	H. E. Inslerman	013D
IV-9	Able and Baker Day Interim Report on the effect of the Atomic Bomb Detonation on HF and VHF Propagation	J. C. Rizos, Maj. AC	013L
IV-10	Able and Baker Day Interim Report on General Propagation Studies Throughout the MF, HF, VHF, and UHF Frequency Spectrums.	Dean C. DeFord Maj. AC Robert C. Trenkle Maj. AC	013L
IV-11	Studies of Airborne Radar in presence of Air and Submarine Atomic Explosions.	William R. Boario	013L
IV-14	Long Range Radio Transmissions	R. A. Jordon LtCdr, USNR	013D
IV-15	Long Range Radar Detection (Able test only)	J. F. Dickson	013D
IV-16	Short Range Radar Detection	G. K. Green	013D
VIII-16	Long Range Radio Propagation	National Bureau of Standards and Federal Communications Commission	013J

SECRET

ENCLOSURE H

"Summary of Radiometric Measurements of Atomic Bomb Tests at Bikini in July 1946"

by

Dr. E.O. Hulburt

SECRET

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Summary of Radiometry Measurements of Atom Bomb Tests at Bikini in July 1946

1. Radiometry measurements of the Atomic Bomb detonations at Bikini were planned by several organizations. The Bureau of Ordnance Radiometry Group obtained results described in the reports listed below. No other organizations reported any results, and it is believed that they did not obtain results. The following summary is based on these reports.

2. Crossroads Technical Instrumentation Reports of the Bureau of Ordnance Radiometry Section:

a. H. S. Stewart and J. A. Sanderson, "Test A, Measurement of Total Radiant Energy."

b. H. S. Stewart and S. S. Ballard, "Test A, Measurement of Spectral Radiance of the Explosion at 3600A and 9400A as a function of Time."

c. C. C. Hauver and E. O. Hulburt, "Test A, Spectrum of Atom Bomb of July 1, 1946 at Bikini."

d. J. A. Sanderson, "Test A, Smoke Cloud Temperature."

e. H. S. Stewart and J. A. Sanderson, "Test B, Measurement of Total Radiant Energy."

f. H. S. Stewart and J. A. Sanderson, "Test B, Illumination Resulting from the Explosion as a Function of Time."

g. S. S. Ballard, "Test B, Spectra of the Atom Bomb Flash."

Test A

3. Thermocouple measurements on a ship and on a plane, each 18 sea mi from Bomb A, gave the following information:

a. The total radiation energy throughout the spectrum was 5×10^5 erg cm^{-2}.

b. The radiation energy in a violet spectral band at 4200A was 8.2×10^3 erg cm^{-2}.

c. The radiation energy in an ultraviolet spectral band at 3600A was 1×10^3 erg cm^{-2}.

4. Spectrograms taken on a ship at 18 sea mi from Bomb A gave the following information:

a. The Bomb A spectrum extended from about 8600 to 3200A, the first limit being due to the spectrographs and the second to the ultraviolet absorption of air.

b. The bomb spectrum contained many absorption lines or bands some of which were identified with oxygen, hydrogen, iron, sodium and perhaps calcium and titanium; not all of the absorptions were identified.

c. The intensity distribution in the bomb spectrum on the photographic plates was a maximum at about 7000A and fell off more rapidly toward the ultraviolet than did the solar spectrum because of the ultraviolet attenuation of the atmosphere.

d. When corrected for the atmospheric attenuation the bomb spectral distribution was approximately in accord with the inverse fourth power of the wavelength, but deviated from this relation in the region 6000 to 4000A. Calculation showed that this result was in agreement with Paragraph 3 (b) and (c) above.

e. The total radiation from 8600 to 3400A received at the spectrographs was 5×10^5 erg cm^{-2}; this agrees with paragraph 3 (a).

5. Photocells on a plane at 18 sea mi gave the following information: Two photocells, on accepting a spectrum band at 9400A and the other at 3600A, were set to trigger off only in the first millisecond by a known amount of energy. They were not triggered by the flash, thus showing that less than about 2% of the energy in the band at 9400A integrated over the total time of the flash, and less than about 7% in the 3600A band, was received in the first millisecond.

6. On the assumption that the Bomb A flash radiated equally in all directions the total energy radiated by the flash was calculated from the value 5×10^5 erg cm^{-2} received at 18 sea mi for an atmospheric attenuation corresponding to a visual range of 23 sea mi. The total energy of the bomb radiated in the spectral region 24,000 to 3400A came out to be

$$1.7 \times 10^{21} \text{ erg.}$$

In like manner the total energy radiated by the Trinity Bomb was calculated for the same atmospheric attentuation, using 1.22×10^7 erg cm^{-2} for the radiated flux at 5 statue mi and assuming that the bomb had for the same spectral energy distribution observed for the Bomb A. The total energy of the Trinity Bomb radiated in the spectral region 24,000 to 3400A came out to be

$$5.7 \times 10^{20} \text{ erg.}$$

It is seen that the energy radiated by Bomb A was about 3 times that radiated by the Trinity Bomb. Assuming that 1 ton of TNT was equivalent to 4.2×10^{16} erg one has for the 2 bombs

Bomb A - 40,000 tons TNT
Trinity Bomb - 13,000 tons TNT

The meaning of the TNT equivalent of the bomb is not clear, because the radiated energy was probably a fraction of the total energy of the bomb explosion.

7. With a thermocouple on a ship at 18 sea mi no thermal radiation was observed from the smoke cloud rising from the bomb explosion of intensity greater than that of the sunlight scattered by Bomb A.

Test B

8. A thermocouple on a ship at 10.9 sea mi from Bomb B gave the following information:

A short pulse of energy was recorded which reached a peak value of about 60 erg cm^{-2} sec^{-1} at about 0.15 sec after the initiation of the blast. The pulse decreased rapidly; the integrated energy received between 0 and 0.6 sec was 14 erg cm^{-2}. The sea horizon was 8.9 sea mi from the thermocouple. Thus the measurement related to radiation emerging from the explosion at points 3 ft and higher above sea level.

9. Spectroscopes on a plane at slant range of 7.2 sea mi and altitude of 9500 ft recorded no spectra of the bomb flash. Photographs of the explosion showed only a relatively small flash emerging above the surface from Bomb B, and it was not surprising that this was too weak to imprint a spectrum on the plates of the spectographs.

TOP SECRET

ENCLOSURE I

"A Critical Summary of Some Test A Shot Measurements"

by

Dr. J.O. Hirshfelder

and

Dr. J.L. Magee

as condensed by

Dr. E.S. Gilfillan, Jr.

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A Critical Summary of Some Test A Shot Measurements

Introduction

This is an attempt to summarize some of the results of the Test A. Except for a written report by Brian O'Brien on the initial brightness of the ball of fire and a brief account of the Radiological Safety Section's gamma radiation measurements (via private communication of James Rouvina), the writers have only had access to the reports of Los Alamos Groups. The Los Alamos work is therefore stressed.

In section I there is a summary of a number of phases of Test A. To make this section as complete as possible, the writers have included things which depend upon their memory of preliminary data and scuttlebutt. This section should not be considered as very reliable. Further information on all phases should be available soon from the Technical Director.

In section 2 an analysis is made of the condenser gauge air blast measurements.

In section 3 the visible and thermal radiation is discussed.

In section 4 the fast neutron measurements are discussed.

In section 5 on gamma radiation, the writers have attempted to collect as much information on the nature of this radiation as is possible at present.

I. Summary of Test A

1.001 Air Blast (Region of Damage)

In the high pressure region, the only gauges which yielded significant results were the Penney tin-cans and harps. The more complicated instruments failed to give records as a result of the failure of the black boxes. The box gauges gave very erratic results because of the diffraction of the blast waves on the sides and superstructures of the ships. The Penney gauges were more reliable because they integrated the pressure over a rather long period of time. Their operation is discussed in the Crossroads Handbook, II-2 and II-3.

The pressure-distance relation determined by the Penney gauges agreed very well with the curve prepared by the Navy Bureau of ordnance by scaling small charges to 20,000 tons of TNT. In order to obtain agreement with the calculations which we had made on the basis of theoretical integration of the hydrodynamical equations for atomic bomb explosions, it would be necessary to assume that the energy yield was equivalent to 30,000 tons of TNT. Since the chemical evidence (which is accurate to ± 10%) points to a yield of 20,000 tons, it appears that one ton of nuclear energy released produces the same amount of blast as one ton of TNT. This result is contrary to our findings at Trinity, where it appeared that one ton of nuclear energy produced energy in blast only equivalent to two-thirds of a ton of TNT. Because of this conflict of the two sets of air blast measurements, no definite conclusion can be drawn at the present time concerning the application of energy going into air blast.

1.002 Air Blast (Parachute Condenser Gauges)

From the parachute condenser gauge records, we can estimate the energy released. This is best done using the shock pressure and correcting for the change of air density with altitude by a new second order approximation of Fuchs. Thus we find from the parachute gauges that the nuclear energy released by Bomb A was 17,000 tons. This figure agrees very well with the 20,000 tons found by the radiochemists. From the radiochemical data, Bomb A and the Trinity Bomb were equally potent. The only good parachute gauge record at Nagasaki (using a new calibration of the Nagasaki record prepared by William Lawrence) gives, on the same basis as Bomb A, 41,700 tons. Similarly with a new calibration prepared by William Lawrence, we get 14,900 tons for the Hiroshima Bomb. Unfortunately, the Hiroshima and Nagasaki records are not supposed to be very accurate, and the above figures are not to be taken too seriously.

The results of the parachute condenser gauges are very difficult to interpret. We shall discuss the problems in considerable detail in a later section of this report. The suction phase of the blast waves was almost entirely missing, and the shapes of the different records varied considerable. Probably the energy of the suction phase was dissipated in the production of condensation. The exact shape of the pressure wave depends in a critical way on the gusts and clouds which the wave has passed through.

1.003 Gamma Radiation

The gamma radiation as a function of distance was measured by Dr. Dessauer by the blackening of x-ray film. He found that the dosage in Roentgens is given by the equation:

$$R = \frac{3.7 \times 10^{10} \times 10^{-R/850}}{R^2}$$

Here R is the distance from the explosion in yards. The exponential attenuation corresponds to a mean free path of 340 meters which is characteristic of 5 million electron volt gamma rays. The lethal distance, i.e., distance at which the dosage is 500 R, is around 1300 yds. This is much closer than the lethal distance reported by the doctors at both Hiroshima and Nagasaki. Preliminary results of the Bikini animal experiments indicate 1500 yds as the distance that an animal has an even chance of surviving. The animal experiments thus agree with Dr. Dessauer's measurements and leave the Japanese observations unexplained. (The British Mission in Japan has estimated that people in the open had a 50% chance of surviving the radiation at the distance of 1300 yds. See "The Atomic Bombings of Hiroshima and Nagasaki" by Manhattan Engineer District, p.34.)

The rate of radiation was measured by Dr. Tuck with recording ionization gauges. His measurements were accurate after the first second. His results indicate that the bulk of the radiation is received during the first 10 sec from the fission products, before they are carried away by the rising of the cloud. We will discuss Dr. Tuck's results in considerable detail in a later section.

1.004 <u>Neutrons</u>

The flux of slow neutrons was measured as a function of distance by Wright Langham, K. Scott, and H. G. Hamilton by means of sodium, phosphorus, and arsenic activations. Their results agree well with the table given in the Crossroads Handbook, I-4. The equation from which this table was constructed contained a misprint and should read:

$$\frac{\text{No. of neutrons}}{\text{cm}^2} = 2.24 \times 10^{12} \times 10^{-(R(\text{meters})/550)^2}$$

Since this equation was based on the observations at Trinity, it follows that the flux of slow neutrons at Bikini and Trinity must have been similar.

1.005 Visible and Thermal Radiation

We have heard results of two sets of measurements of the visible radiation. One was a spectroscopic observation of the time integrated radiation made by E. O. Hulburt of the Naval Research Laboratory. He found that the spectral distribution and intensity at a distance of 36,000 yds was almost exactly equivalent to the sun shining for a duration of one second. At this distance, the formula given in the Crossroads Handbook, 1-4, leads to an expectation of 0.73 suns per second. The agreement is therefore excellent.

The size and brightness of the ball of fire were measured by Brian O'Brien et al with a streak camera. From the size as a function of time, he was able to use the equations given in the Crossroads Handbook, II-4, to compute the energy released by the bomb as equivalent to 21,300 tons of TNT. This is in excellent agreement with the radiochemical data. The peak intensity of illumination corresponds to a temperature of 200,000°C at a time of 120 microseconds. Such a temperature had been predicted (Crossroads Handbook, VI-1), but it should have occurred somewhat earlier. The rate of decrease of temperature was in good agreement with the predictions.

Many samples of fabrics and paints were exposed to the heat. The charring occurred out to a distance of around 1500 yds. The amount of charring agreed with the fraction of the light which would be absorbed by virtue of the color and roughness of the fabric. The nature of the material also played a role. The mechanism for this charring seems to agree with the expectations of Crossroads Handbook, VI-1.

1.006 Cloud Formation

Afte Bomb A had exploded and the shock wave had moved to a great distance, there remained a spherical region of hot air which started to rise immediately, due to the action of gravity. In rising, it sucked in cool air from the surroundings and was itself cooled. The cloud after Test A was similar in most respects to that after the previous shots. In place of the large amount of dust present in the Trinity cloud, the Test A cloud sucked up a large amount of moisture and spray. This moisture soon condensed into a heavy vapor and froze into little ice crystals at a level of over 18,000 ft. The cloud was given an apricot tint by the combination of the nitrogen dioxide formed in the explosion and the glow of the active nitrogen recombination spectrum (the active nitrogen is formed whenever air is ionized). Contrary to advance predictions, the cloud only rose to around 40,000 ft. Since Bomb A released the expected amount of energy, it follows that the cloud must have sucked in a larger volume of the surrounding air than expected. This greater amount of mixing might be explained by the high winds and gusts.

The active material was deposited on the water droplets which remained in the air. There was no evidence of abnormal rain from the cloud or of a trail of active material produced by a fall-out. This was quite different from the situation at Trinity where the active material was deposited on dust particles which fell according to Stoke's law.

1.007 Cloud Chamber Effect

Whenever the humidity is over 80%, it may be expected that there will be condensation produced by the cooling of the air in the suction phase of the blast wave. This cloud chamber effect only occurs at a particular stage of the blast. Since the humidity was around 83% at the time of the Bomb A detonation, a cloud chamber effect was observed for a period of about a second. This appeared as a sort of soap bubble surrounding the target area and quickly disappeared. This effect was predicted in Crossroads Handbook, I-3.

1.008 Height of Waves

In agreement with advance predictions, only small waves were produced, they were completely damped out before they reached Bikini Island three and a half miles from the target area.

1.009 Radioactive Marbles on PRINZ EUGEN

A large number of radioactive iron pellets were found on the afterdeck of the PRINZ EUGEN. These were rapidly collected as souvenirs by a great many people and were made a subject of great curiosity. They were undoubtedly a part of the GILLIAM, which was in the ball of fire, and thrown to large distances. Obviously, these marbles could not have been a part of the bomb case as was generally supposed by the newspaper reporters.

1.010 Damage to Ships

The damage to ships as a function of the blast pressure followed rather close to Dr. Penney's predictions. It is still believed that 100 psi shock pressure would be sufficient to sink a capital ship. After Test A, only the superstructures were seriously damaged. The funnels of many ships were caved in and the boilers were destroyed. If the ships had been under steam, the boilers would have exploded causing considerable damage and casualties.

2. CONDENSER GAUGE MEASUREMENTS

2.001 Introduction

The parachute condenser gauges can be used to make a good estimate of the energy released in the atomic bomb explosions. There are a number of different ways in which the records can be used for this purpose. For example, the shock pressure, the positive pulse, the energy remaining in the blast, and the duration of the positive pulse each indicate the magnitude of the explosion. Of these, the shock pressure probably gives the most reliable results. The size of the air vent in the gauge can effect the decay of the blast, but it does not effect the indicated value of the shock pressure. The slant distance of the gauge from the explosion is best determined from the elapsed time between the bomb drop and the arrival of the blast. The correction of the pressure for altitude is best made with a second order theory of Fuchs which takes into account the energy dissipation of the blast. The difference between the energies calculated on this basis and the ones calculated with the acoustical theory are quite appreciable. Thus we find that in Test A there was 17,000 tons of TNT energy released, and in Test B the blast was equivalent to an air burst in which 11,750 tons of TNT energy was released.

Using a new set of calibrations for the Hiroshima and Nagasaki gauge records prepared by William Lawrence together with the Fuchs altitude corrections so that all of the methods of calculation are the same as for the Bikini Tests, we find from the shock pressure:

Test A E(nuclear) = 17,000 tons
Nagasaki E(nuclear) = 41,700 tons
Hiroshima E(nuclear) = 14,900 tons

In Test A, the radiochemists found that approximately 20,000 tons of TNT energy were released, therefore the results of the condenser gauges appear to be reasonable close to the correct energy yields.

However, the condenser gauge records are difficult to interpret because:

(1) We do not have an accurate knowledge of blast pressure versus distance for either the normal TNT explosions or for the atomic bombs. We do have rough equations for both and analyze the data on both bases.

(2) The altitude correction is hard to make since it depends critically on the temperature, humidity, and gusts which the blast passes through. This correction is so sensitive that the records of two parachute gauges falling a few hundred feet apart may differ considerable even as to shape. We make the corrections on the basis of the new Fuchs approximations.

(3) In Test A, there was a discrepancy of around a mile and a half between the distance indicated from the radars and the distance computed from the elapsed time. Since it is very difficult to imagine large errors in the elapsed time, we have disregarded the radar distance.

On most of the records, the suction phase was washed out. This was probably due to the cloud chamber effect. The cooling of the air in the suction phase caused condensation. The condensation releases heat which increases the pressure and washes out the suction phase.

2.002 Test A

Four gauges were dropped from two planes. All of the gauges were at approximately 26,800 ft altitude at the time of detonation. Gauge 17 gave the clearest record. The record trace on gauge 13 was fuzzy, but readable. Gauge 18 gave a good trace except for the early moments when it was apparently off scale, and it is necessary to extrapolate back to zero time. Gauge 3 apparently developed an air leak in the microphone, and its record should be discounted.

At the time of the shot:

Temperature at sea level = 29° C

Pressure at sea level = 1012 millibars

Temperature at 26,800 ft = - 20° C

Pressure at 26,800 ft = 374 millibars

The primary data from the records are given below:

Gauge No.	Shock Pressure (psi)	Positive Impulse (psi-sec)	Integral of Square of Pressure in Positive Phase (psi^2-sec)	Duration Positive Phase (sec)	Time Between Drop and the Shock (sec)	Slant Distance to Explosion from Elapsed Time (feet)
17	0.168	0.126	0.0143	1.59	77	33,300
18	0.178	0.141	0.0165	1.62	79	35,450
13	0.150	0.116	0.0119	1.61	83	39,800

The distances given in the above table were obtained in the following manner. First, 48 sec were substracted from the time between the drop and the shock to give the time, t_s, between the detonation and the reception of the shock by the gauge. Then the distance was computed by taking the velocity of the shock equal to the velocity of sound after the first few seconds. The constant 1665 corrects for the greater speed of the shock during the first few seconds. The factor

$$((1 + T_h/T_g)/2)^{1/2}$$

corrects the velocity of sound for the colder air at the higher levels. Thus the slant range, R (ft) is given by the relation:

$$R(ft) = (1140\ t_s + 1665)\ ((1 + T_h/T_g)/2)^{1/2}$$

The distances given by the radar are: 7,900 ft, 5,750 ft, and 4,000 ft greater than the time elapsed distances for the records of gauges 17, 18, and 13 respectively.

A. Analysis Using Simple Acoustical Theory for Altitude Correction

Using simple acoustical theory to correct for the change in density and temperature with altitude, we can determine the apparent energy yield from the shock pressure, from the positive impulse, and from the energy in the positive phase of the blast. The effect of the altitude comes into the factor, f:

$$f = ((\rho_h c_h)/(\rho_g c_g))^{1/2} = (P_h/P_g)^{1/2.8}\ (T_h/T_g)^{0.25}$$

For the height of 26,800 ft and the conditions of Test A,

$$f = 0.670$$

It is convenient to define W as twice the equivalent energy released in pounds of TNT. Thus the energy released, E, expressed in tons of TNT is given by

$$E = W/4000 \text{ tons.}$$

There are now two ways to analyze the data. If we make use of the IBM calculations, we can estimate how much NUCLEAR energy was released, E(nuclear). Or, if we take the normal scaling laws for TNT explosions, we can get the energy in the blast equivalent to that produced by E(TNT) tons of normal explosive. Because of inaccuracies in the IBM calculations, the ratio between the two quantities is not significant. At the present time it has not been difinitely decided whether E(nuclear)/ E(TNT) is 2.0, 1.5, or 1.0. We will present both types of analyses and not pass on their significance.

1. Determination of E(nuclear) from IBM pressure-distance curves.

(1) Shock Pressure

$$P_s(\text{psi}) = \frac{27.40f}{X\ (\log_{10}X-0.662}\quad 1/2$$

Here and in the subsequent treatment

$$X = R/W^{1/3}$$

(2) Duration of the positive pulse

$$(\text{seconds}) = 0.0023\ W^{1/3}\ (\log_{10} X - 0.662)^{1/2}$$

(3) Positive Impulse

$$I(\text{psi-sec.}) = 0.035\ f\ W^{2/3}/R$$

(4) Energy in the positive pulse of the blast.

The energy in the positive pulse of the blast, E_{b1} (tons TNT), may be written

$$E_{b1}\ (\text{tons TNT}) = 1.319\ (R/300)^2\ f^{-2}\quad P^2\ (\text{psi})dt$$

Thus E_{b1} is determined from the integral of the square of the pressure with respect to time. Then W is determined from the relation:

$$E(\text{nuclear}) = 20E_{b1}(\text{tons TNT})\ (\log_{10}X - 0.662)^{1/2}$$

Using these relations together with the primary data, we obtain the following results:

Gauge	**E_{bl}**	**E(nuclear), tons TNT**			
		From P_s	From τ	From I	From E_{bl}
17	517	10,700	60,800	18,900	11,450
18	677	14,900	62,300	24,600	15,160
13	616	13,610	57,500	21,800	14,060

2. **Determination of E(TNT) from normal TNT pressure-distance curves.**

(1) Shock Pressure

$$P_s \text{ (psi)} = \frac{35\ f}{X(\log_{10}X - 0.928)^{1/2}}$$

(2) Positive Impulse

$$I\text{(psi-sec)} = 0.0545\ f\ W^{2/3}/R$$

(3) Energy in the Positive Pulse of the Blast.

$$E(TNT) = 11.9\ E_{bl}\ (\log_{10}X - 0.928)^{1/2}$$

Using these relations together with the primary data and E_{bl}, we obtain the following results:

Gauge	**E(TNT), tons TNT**		
	From P_s	From I	From E_{bl}
17	4200	9700	6540
18	6290	12700	8770
13	5725	11200	7440

B. **Analysis Using Fuchs' Second Order Corrections for Altitude.**

Recently, Fuchs developed a set of corrections for altitude taking into account the dissipation of energy of the blast wave due to variations in the density and temperature of the air. This correction is a considerable improvement on the simple acoustical theory. Fuchs has written up the derivation of his results in the Los Alamos Encyclopedia

$$E(\text{nuclear}) = 20\ E_{bl}\ (\text{tons TNT})\ (\log_{10}(\lambda X) - 0.662)^{1/2}$$

It is interesting to note that the equation for the positive impulse remains unchanged. Using these equations together with the data given, we obtain the following results:

Gauge	E(nuclear), tons TNT			
	From P_s	From τ	From I	From E_{bl}
17	14,050	41,600	18,900	13,000
18	19,190	46,150	24,600	16,740
13	17,870	41,140	21,800	15,710

2. Determination of E(TNT) from normal TNT pressure-distance Curves.

(1) Shock Pressure

$$P_s(\text{psi}) = \frac{35f}{X(\log_{10}(\lambda X) - 0.928)^{1/2}}$$

(2) Positive Impulse of the Blast

$$I(\text{psi-sec}) = 0.0545\ f\ W^{2/3}/R$$

(3) Energy in the Positive Pulse of the Blast.

$$E(\text{TNT}) = 11.9\ E_{bl}\ (\log_{10}(\lambda X) - 0.928)^{1/2}$$

Using these results together with the given data, we obtain the following results:

Gauge	E(TNT), tons TNT		
	From P_s	From I	From E_{bl}
17	5,850	9,700	7,380
18	8,115	12,700	9,550
13	7,150	11,200	8,790

2.003 Test B

Just before the underwater explosion in Test Baker, four parachute condenser gauges were dropped each at a height of 23,600 ft and at a slant distance of 42,500 ft. One of the gauges, Channel 16, developed an air leak in the microphone, and we will therefore disregard its record. The gauge with Channel 5 gave the best record. The gauges with Channels 1 and 7 gave records slightly off scale and have to be extrapolated back to zero time.

The primary data from the records are given below:

Channel No.	Shock Pressure (psi)	Positive Impulse (psi-sec)	Duration Positive Pulse (sec)	Energy in Positive Pulse (tons TNT)
5	0.136	0.082	1.25	389
7	0.128	0.085	1.34	376
1	0.122	0.070	1.20	298

Temperature at sea level = 27° C

Pressure at sea level = 1010 millibars

Temperature at 23,600 ft = -14°C

Pressure at 23,600 ft = 428 millibars

$f = 0.7094$ $\lambda = 1.723$

Using the above information together with the equations given in connection with Test A, we obtain the following results:

A. Analysis Using Simple Acoustical Theory for Altitude Correction.

Channel No.	E(nuclear), tons TNT			
	From P_s	From I	From E_{bl}	From τ
5	11,110	13,150	9,260	23,810
7	9,500	13,880	9,040	28,470
1	8,400	10,370	7,840	20,040

Channel No.	E(nuclear), tons TNT From P_s	From I	From E_{bl}
5	4,550	6,770	5,230
7	3,940	7,140	5,120
1	3,460	5,340	4,070

B. Analysis Using Fuchs' Second Order Correction for Altitude.

Channel No.	E(nuclear), tons TNT From P_s	From I	From E_{bl}	From γ
5	13,500	13,150	9,890	19,550
7	11,650	13,830	9,670	23,240
1	10,090	10,370	7,650	16,690

	E(TNT), tons TNT From P_s	From I	From E_{bl}
5	5,690	6,770	5,640
7	4,890	5,340	4,390

2.004 Nagasaki and Hiroshima

The energies of the Hiroshima and Nagasaki bombs can be estimated from the parachute gauge records. William Lawrence has made a new calibration for the gauges. We have the following primary data:

	Hiroshima	Nagasaki
Height of gauges	30,500 ft	30,500 ft
Slant Distance	40,000 ft	36,000 ft
Shock Pressure	0.089 psi	0.15 psi
Duration Positive Pulse	1.25 sec	1.25 sec
Calculated by Fuchs) → f=	0.5706	f = 0.5706
	λ = 2.527	λ = 2.527

Since the shocks at both Hiroshima and Nagasaki recorded on the gauge records were double, i.e., the reflected shock had not caught up with the incident shock, it was necessary in the above calculations to consider:

$$E(\text{nuclear}) = W/2000$$

The duration for the Hiroshima shock is obviously out of line.

3. VISIBLE AND THERMAL RADIATION

3.001 Total Radiation

The measurement by Dr. E.O. Hulburt of the time-integrated spectral distribution is the only measurement known to the writers bearing on the total radiation. At 36,000 yd the measurement was about one sun-second or possibly a little more. Calculating with the Handbook formula (Section I-4) one gets 0.73 sun-seconds. Since the theoretical formula neglects atmospheric attenuation it would appear that the total radiation was somewhat higher than predicted.

3.002 Time - Temperature - Radius Relation

A measurement made by Brian O'Brien et al[1] by means of a high speed streak camera gave the radius of the ball of fire and its absolute brightness during the first eight milliseconds. Only one record was obtained. The radius-time relation is the result which is easiest to obtain from this record; it is given in Figure 1. For the first millisecond, this curve does not give the relation,

$$R \propto t^{2/5}$$

as predicted for strong shocks. Between 1 and 9 milliseconds, however,

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[1] A Crossroads Technical Instrumentation Report to the Technical Director, August 21, 1946.

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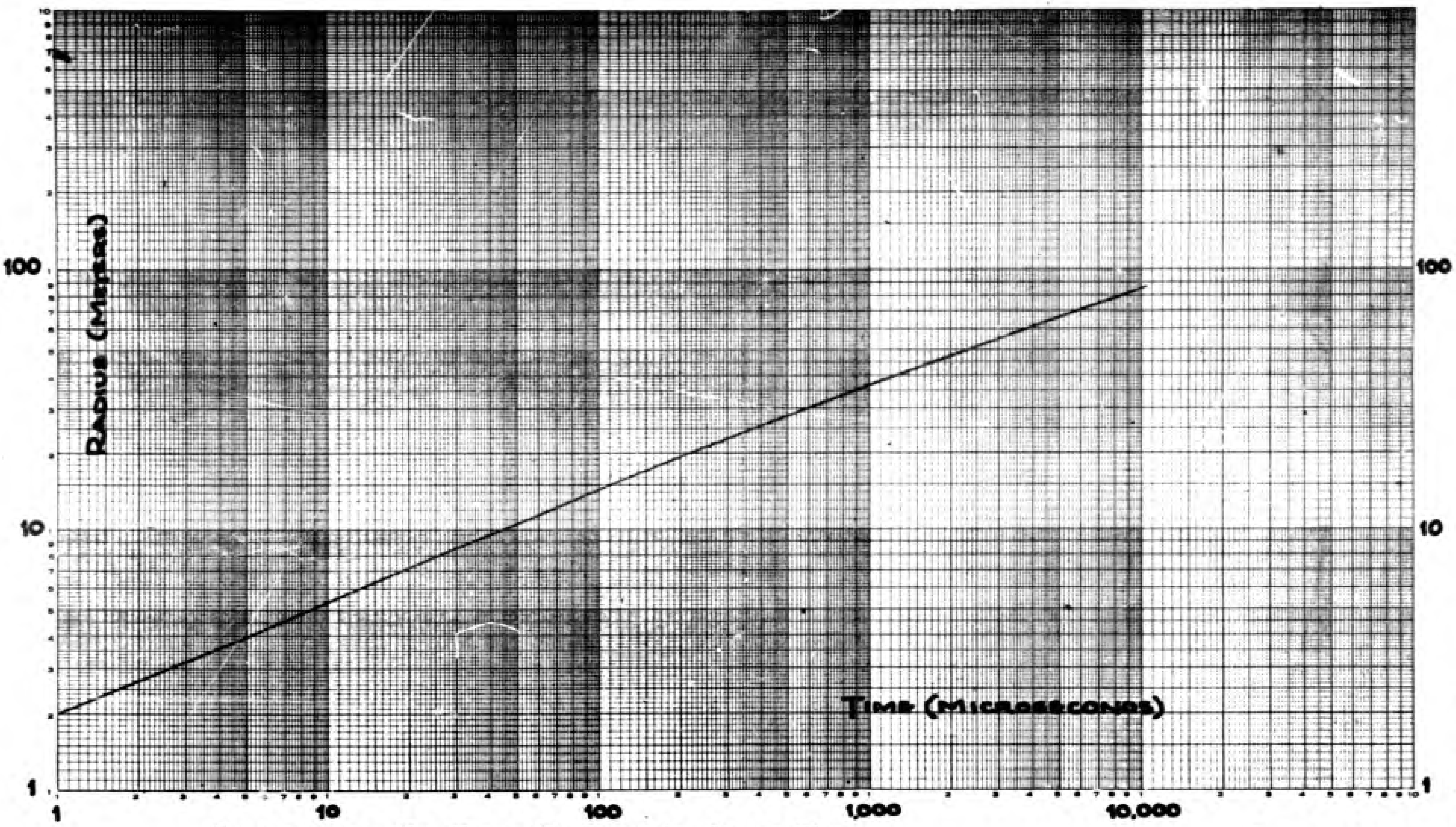

EXPANSION OF BALL OF FIRE IN ABLE TEST

FIGURE 1

the slope is correct. Using the curve during this period, one calculates 21,300 tons TNT as the equivalent yield with the Handbook formula (Section II-4).

The absolute brightness as a function of time was also obtained by measuring the absolute intensity of the light at 6,400 A°. O'Brien's original results (in multiples of the solar brightness) have been converted into temperatures of the radiating surface treated as a black body. The temperature-time relation is given in Figure 2. This result is the first confirmation of the high temperatures (~200 000° K) predicted by theory. The results of J.E. Mack et al at Trinity only indicated temperatures of the order of 15,000° K, although the estimate was admittedly very rough and not self-consistent.

The surprising result of Figure 2 is that the temperature builds up so slowly. The predicted high temperatures should be reached in about 10 microseconds whereas it seems to take about 100 microseconds. The theory of the origin of the shock in air has been discussed.[2]

According to this theory, the first phase of the ball of fire occurs by a radiative transfer mechanism; the radius grows to about 12 meters during this phase. Rather suddenly a strong shock wave in air develops, and then the radiative effects in energy transfer become less important than hydrodynamical effects. At all times the effective temperature which one sees (at any wave length) is the temperature existing at an optical depth within the heated body. It had always been thought that this temperature should be very high, but the calculation depends in a critical manner on the opacity of air. This problem will have to be reconsidered, using a more accurate value of the opacity as a function of temperature

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[2] Magee and Hirschfelder in Los Alamos Technical Series, Vol. 7, Ch. 4.

3.003 Comparison of Observed Temperatures with the IBM Calculation

In so far as there is true "similarity" for strong shock waves in air, one expects that the properties of the shock front are only a function of $R/W^{1/3}$, R being the shock radius and W being the energy yield. For this reason we compare the radius at which a given temperature was observed in Test A to the radius predicted by the IBM calculation for 20,000 tons TNT. This is done for a number of points for temperatures past the maximum, where it is expected that the temperatures observed should correspond to that of the shock front itself.

Time Milliseconds	T	R_1 (O'Brien)	R_2 (IBM)	R_1/R_2	W_1/W_2
0.15	184,400	17.0	13.8	1.23	
0.30	119,250	22.8	16.4	1.39	
0.6	64,770	30.0	20.4	1.47	
1.0	40,000	36.0	26.5	1.36	2.52
2.0	21,800	47.0	40.2	1.17	1.60
3.0	16,300	55.0	45.4	1.21	1.77
4.0	13,000	62.0	48.7	1.27	2.05
5.0	10,360	66.0	53.1	1.24	1.91
6.0	9,240	70.0	57.5	1.22	1.82
7.0	7,340	75.0	62.3	1.20	1.73

It is clear that the Test A shock would correspond to a larger energy yield than 20,000 tons of TNT according to the IBM calculation. An average of the last 7 values in the table gives W_1/W_2 (which is equal to $(R_1/R_2)^3$) equal to 1.91, or an energy yield equivalent to 38,000 tons TNT. The IBM calculation is admittedly rough, but this discrepancy appears to be quite large. If O'Brien's photographic densities are too

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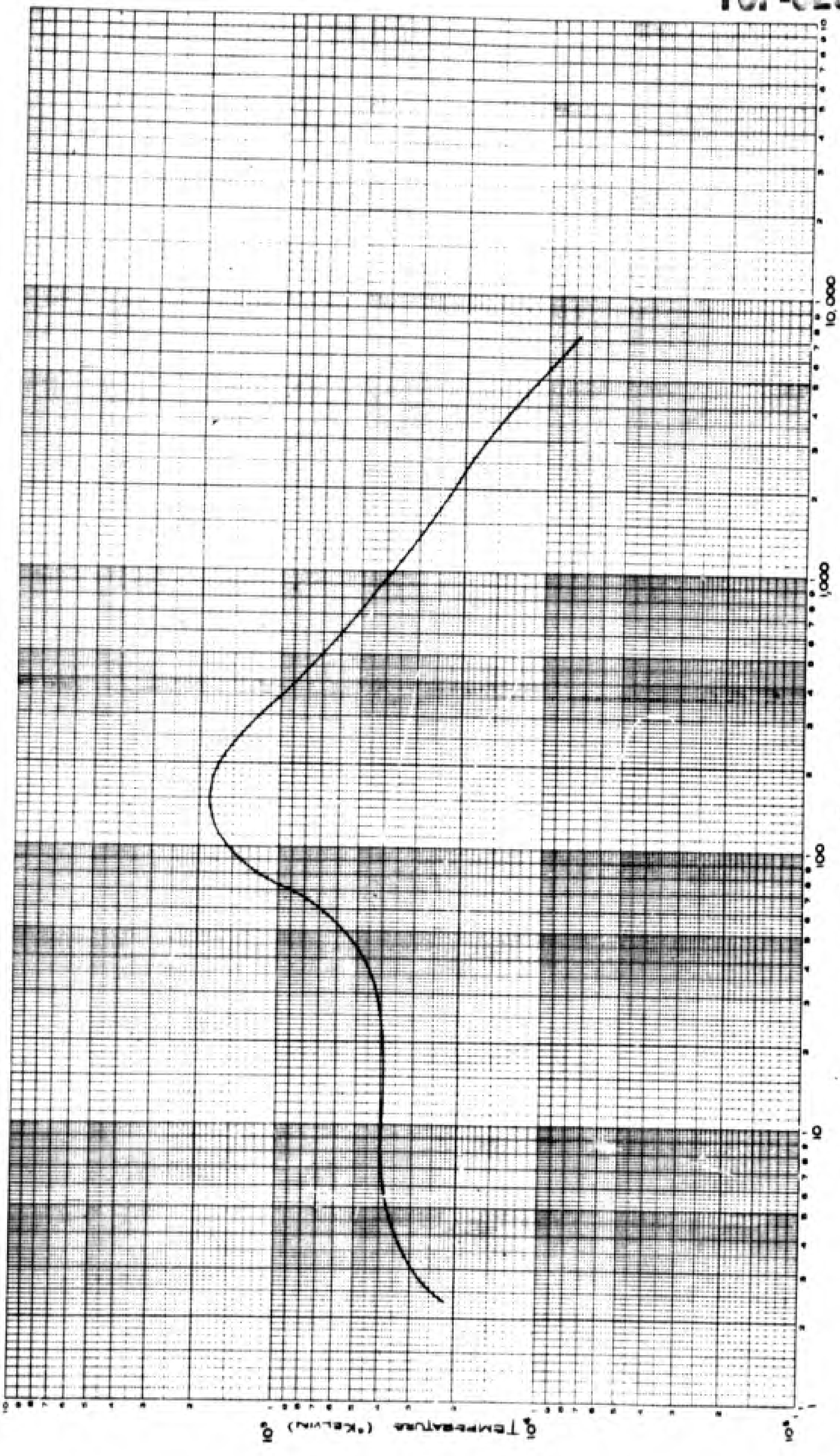

Temperature Of Radiating Surface In Able Test

Figure 2

high for any reason at all (due to development, improper correction for atmospheric attenuation, for example), this would tend to bring better agreement. At present it would be impossible to reconcile the two sets of data.

4. FAST NEUTRON MEASUREMENTS

4.001 Experimental Curve

The experimental measurements of fast neutrons were made for Test A by G. A. Linenberger and William Ogle. Their results are shown in Figure 3. On this same figure is given a single measurement at 220 yd made by E. Klema (LA-361) at Trinity. All of the measurements in Test A were at distances greater than 500 yd. The ordinate in Figure 3 is the number of counts per minute times the square of the slant distances in yards for a forty gram sample as measured in E. Klema's counter, all reduced to zero time. At large distances, this ordinate decreases exponentially with distances, as it should. The e-folding distance or mean free path is found to be 161 yd. However, at distances smaller than 800 yd, the ordinate decreases slower than exponentially as would be expected on the basis of multiple scattering. In fact, we can argue that the curvature corresponds to the neutrons being scattered more than 6 times before their energy is reduced below the 3 MEV threshold of the sulphur. Since, from simple age theory, the energy of a neutron is reduced on an average by a factor of 0,872 every time it is scattered by an air molecule, it follows that the original energy of the neutrons would have to be more than 6 MEV in order to explain the data. Since 6 MEV seems somewhat high, the alternate explanation is that E. Klema's Trinity value is somewhat low.

The reason for believing that the curvature on Figure 3 corresponds to more than 5 scatterings is the following. If we assume that all of the neutrons are scattered in the forward direction, then we calculate the results shown in Figure 4. The observed points fall on the 6 scattered curve. If the neutrons were scattered away from the forward direction more scatterings would be required in order to have the observed curvature.

4.002 Multiple Scattering Treatment

A simple theory which probably gives a lower limit on the number of scatterings which a neutron must suffer, on the average, before being degraded below 3 MEV can be described briefly. We consider neutrons of average energy E(above 3 MEV) and assume that the scattering cross section as a function of the energy is just a constant σ. All neutrons are scattered forward with a fixed percentage degradation of energy per collison. Since neutrons actually suffer more like spherical scattering, this should give an upper limit on the number of neutrons of a given energy which reach a given slant range. The number of neutrons of the original energy E per unit solid angle we shall call N_0. The slant range is R. Then:

$$\frac{dN_0}{dR} = -\sigma N_0 \qquad (1)$$

and $$N_0 = \text{const.}\, e^{-\sigma R} = e^{-\sigma R} \qquad (2)$$

For simplicity, we shall take the constant equal to unity. The differential equation which the first scattered beam satisfies is:

$$\frac{dN_2}{dR} = \sigma N_0 - \sigma N_1 \qquad (3)$$

which gives

$$N_1 = \sigma R\, e^{-\sigma R} \qquad (4)$$

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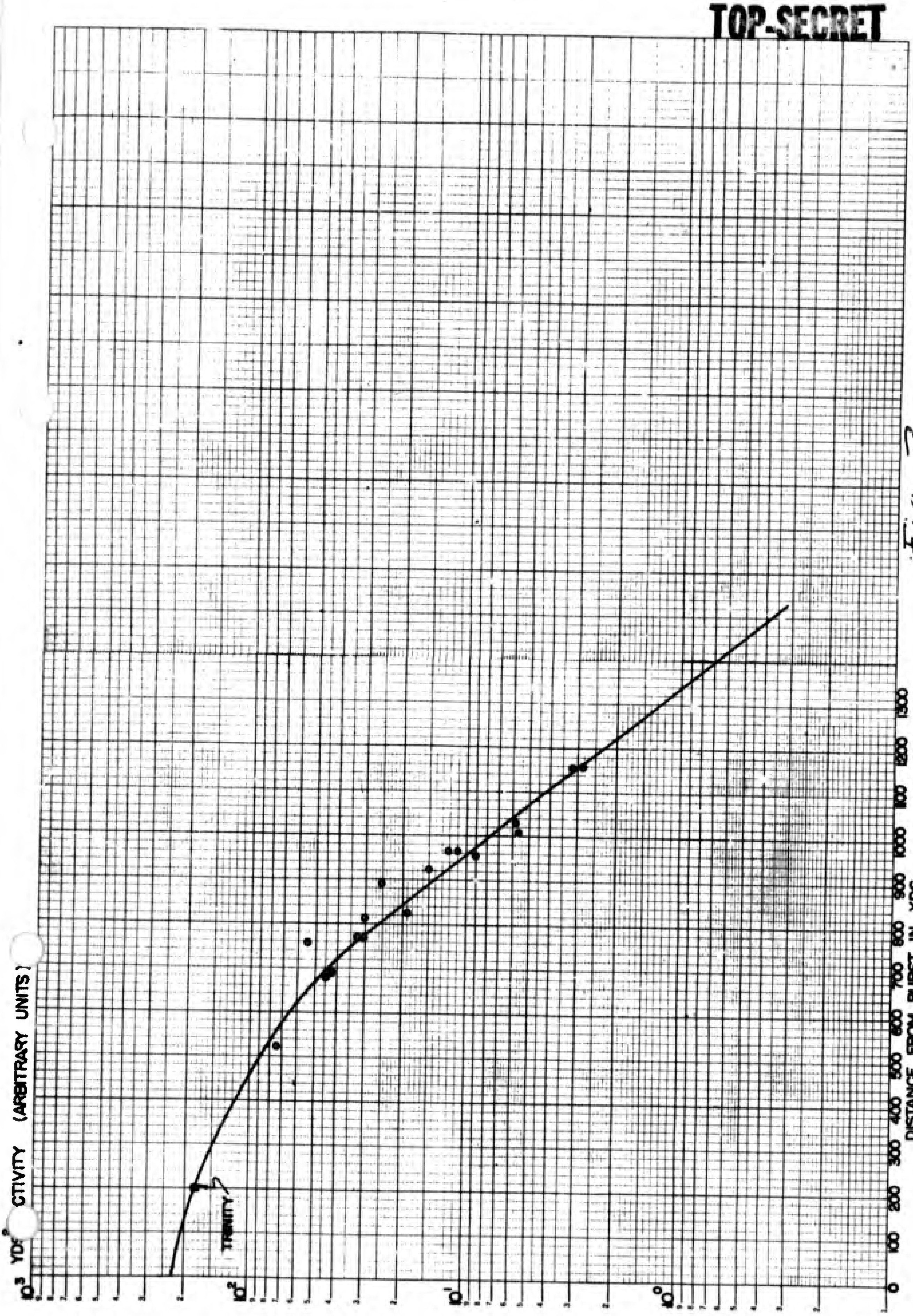

Fig. 3

The second scattered beam is easily found to be:

$$N_2 = 1/2 \quad (\sigma R)^2 e^{-\sigma R} \qquad (5)$$

and in general, the nth scattered beam is:

$$N_n = \frac{1}{n} \quad (\sigma R)^n \quad e^{-\sigma R} \qquad (6)$$

If the first n scattered beams are above 3 MEV, then the activity results should give the sum:

$$I_n = N_0 + N_1 + N_2 + \ldots\ldots\ldots\ldots + N_n = \left[1 + \sigma R + 1/2(\sigma R)^2 + \cdots + 1 \; (\sigma R)^n\right] e^{-\sigma R} \quad (7)$$

Absolute values of I_n as a function of n have been calculated. Clearly on this model a semi-log plot is not a straight line, but continues to increase its slope continuously. The calculated curves have been adjusted for such values of σ that they have unit slope for

$$0.1 \leq 1_n \leq 0.01$$

Curves constructed in this manner for n = 0 to n = 6 are shown in Figure 4. The experimental points of Linenberger and Ogle are plotted on this figure, normalized so that the Trinity point is unity. It seems that one must use a theory which allows at least 5 or 6 scatterings in order to explain the results.

5. GAMMA RADIATION

5.001 Radial Dependence of Total Radiation

The total dose of gamma radiation was measured by Dr. Dessauer and Mr. Rouvina of the Radiological Safety Section using x-ray film. Their results are shown in Figure 5.[3] Here the ordinate is

$$D^2R$$

(distance squared in yards times dose in Roentgens), and the abscissa

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[3] This figure was obtained from Mr. Rouvina in advance of their final report.

is slant range in yards. Each point represents the highest value obtained upon some particular ship. The experimental error was quite small compared to the scattering of the points (probably about 15% or 20% would be a limit to this error), so it appears that even the most exposed films on some of the ships must have been quite well shielded.

If the radiation contains a relatively large fraction of a rather higher energy component than the remainder, one would expect an asymptotic behavior as:

$$D^2R = A \times e^{-D/\Lambda} \qquad (8)$$

where A is constant and Λ is the mean free path. The solid line in the figure represents a curve one might draw as representing the data. Its equation is:

$$D^2R = 3.70 \times 10^{10} \times 10^{-D/850} \qquad (9)$$

The high point at 3500 yd was given by a film taken from a ship which had a fire, and this film was probably ruined by heat.

Closer in, one expects that the dosage is higher than that given by equation (9) because of the added contribution of the lower energy components.

There are two other measurements to compare with Dr. Dessauer's results: the Trinity values (E. Segre' et al, LA-432) and the film found at Hiroshima by Dr. Philip Morrison. These points have been plotted on Figure 5. The two Trinity points are marked with T's and the Hiroshima point with an H. The Trinity points have been corrected for the smaller density of air; and the Hiroshima point has been corrected for a smaller fission yield (8000 tons were used).

Dr. Tuck's ionization gauge values (obtained by integrating his

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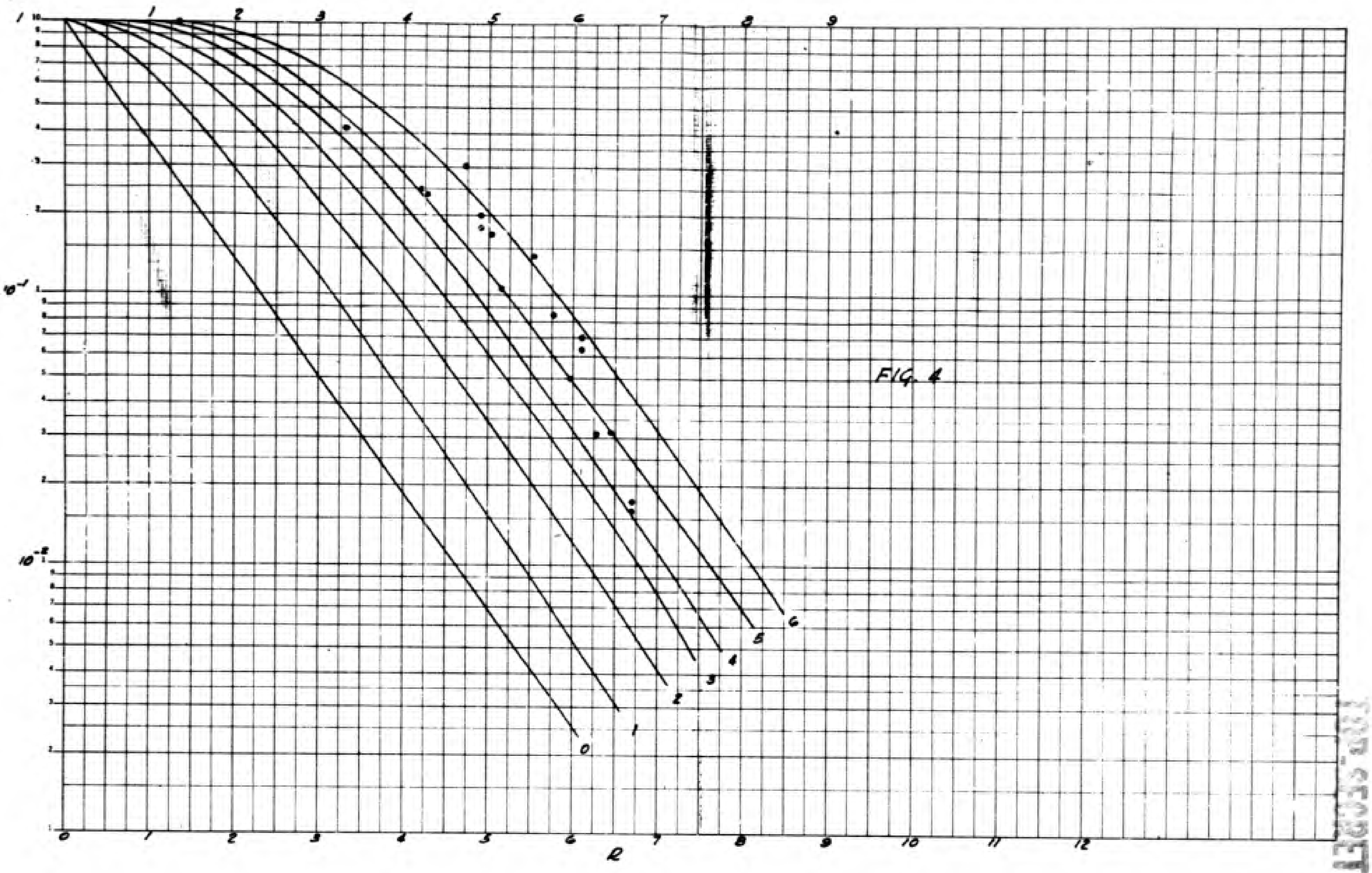

FIG. 4

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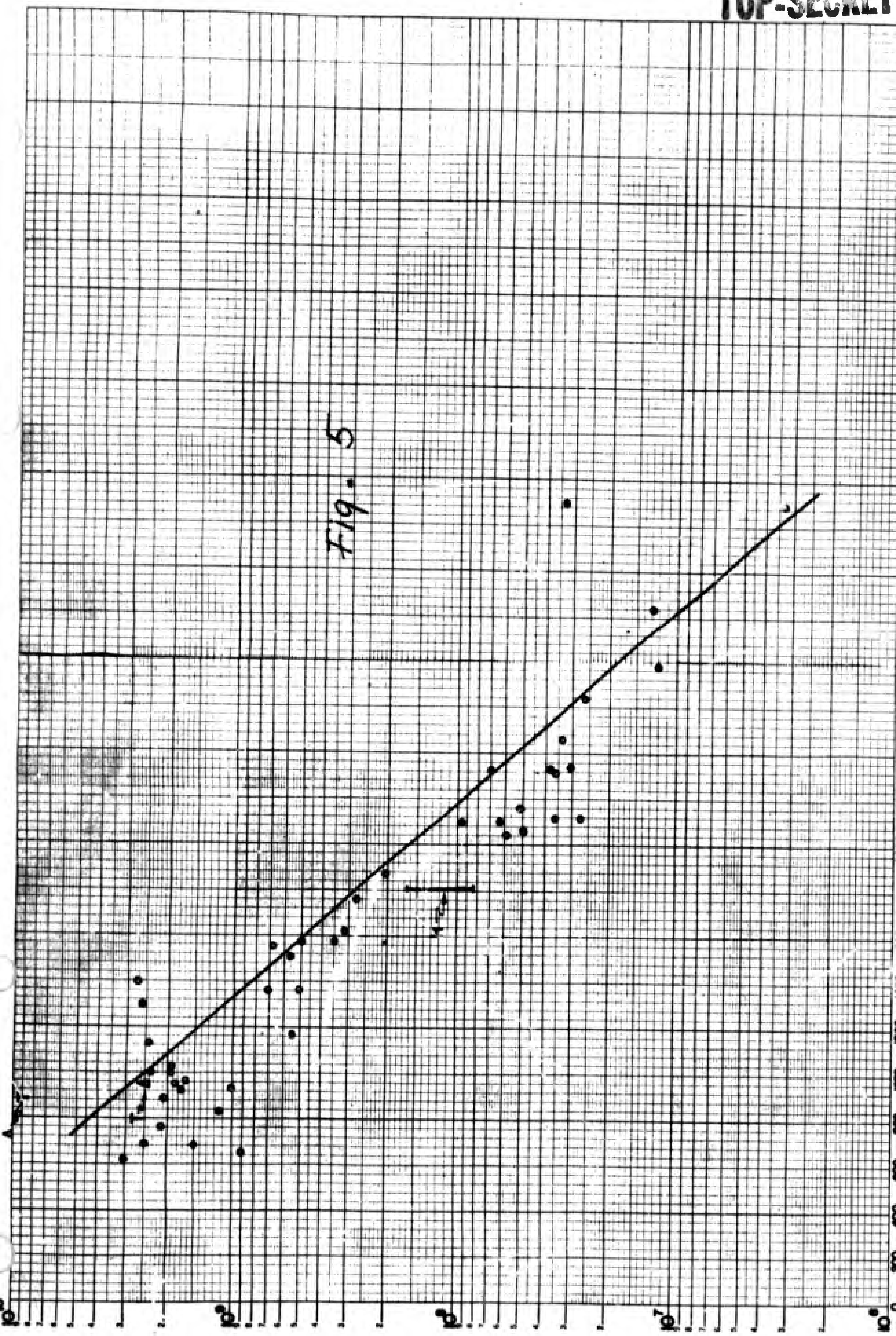
Fig. 5
YDS^2 x R NTGENS
10^4
10^5
10^6
10^7
10^8
DISTANCE FROM BURST IN YDS
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000

FIG 6

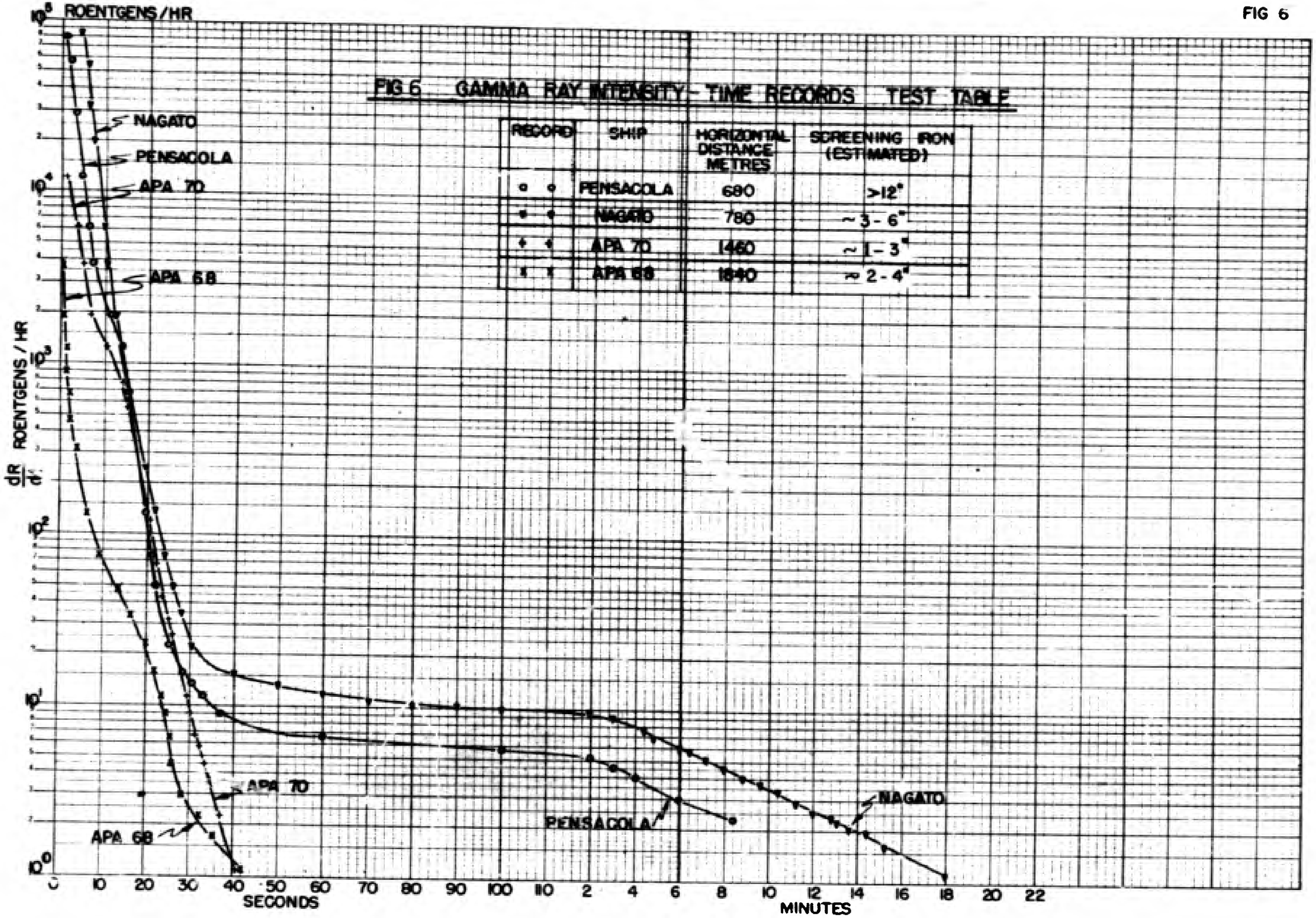

FIG 6 GAMMA RAY INTENSITY - TIME RECORDS TEST TABLE

RECORD	SHIP	HORIZONTAL DISTANCE METRES	SCREENING IRON (ESTIMATED)
o o	PENSACOLA	680	>12"
● ●	NAGATO	780	~3 - 6"
+ +	APA 70	1460	~1 - 3"
x x	APA 68	1840	≈ 2 - 4"

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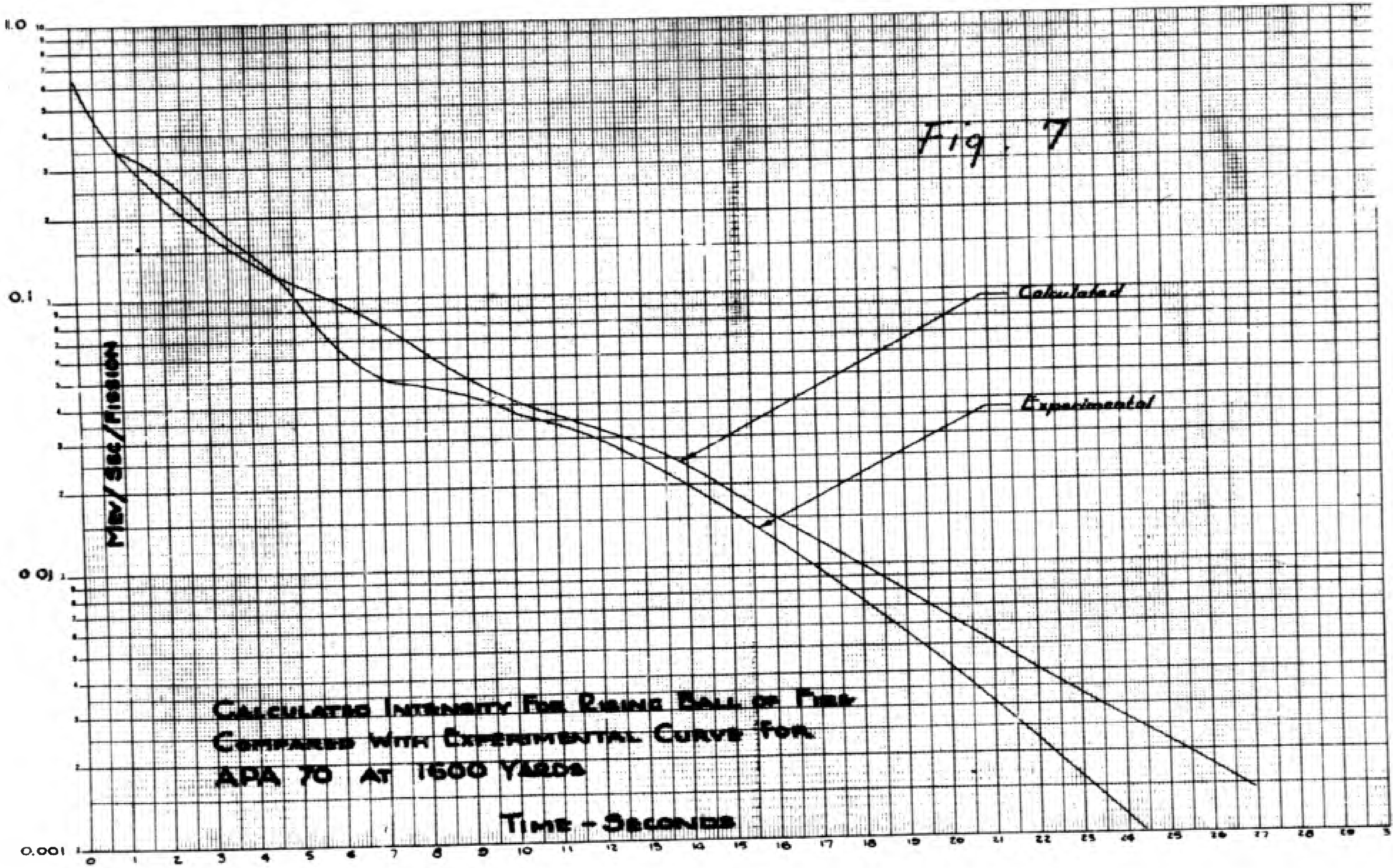

Fig. 7

CALCULATED INTENSITY FOR RISING BALL OF FIRE
COMPARED WITH EXPERIMENTAL CURVE FOR
APA 70 AT 1600 YARDS

intensity-time curves which will be discussed in the next section) will not be used since these gauges were shielded by rather large and uncertain thicknesses of iron.

The total radiation should be checked, at least to a certain extent by the animal experiments. Capt. Draeger (Navy) estimated the distance at which an exposed animal has a 50-50 chance of living at 1500 yd. He would assign a dose of 300-400 Roentgens for this distance. The 50-50 distance at Hiroshima and Nagasaki for human victims[4] was given at 3/4 mi or 1320 yds. The radiation intensities from Figure 5 for these two distances are:

1320 yds - 574 R

1500 yds - 275 R

Although it is generally believed that the efficiencies of the 2 bombs were different, no significant difference in radiation effects was reported. This only indicates the roughness of physiological data.

One can summarize the total intensity data by saying that there is rough agreement of all measurements.

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[4] See "The Atomic Bombings of Hiroshima and Nagasaki" by the Manhattan Engineer District, p. 34.

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ENCLOSURE J

"Nuclear Radiation Effects in Test A and Test B - Preliminary Report"

Prepared by

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Ensign H. W. Walton

Approved by

Colonel S. L. Warren

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Nuclear Radiation Effects in Test A and Test B - Preliminary Report

A. Abstract.

1. For both Test A and Test B a number of different projects were initiated to measure the gamma radiation and neutron flux resulting from the explosion of an atomic bomb just above and under the surface of the water. The sources of nuclear radiation from the explosion are discussed briefly with emphasis on the information which is of practical importance in evaluating the effects of the bomb.

2. In Test A practically all the radioactive material was carried to high altitudes and dispersed downwind so that the residual activity in the waters of the Lagoon and on the target ships was small, and due almost entirely to activity induced by the neutrons from the explosion. The gamma dosage was lethal in the open at a distance of 1400 yd but personnel protected by more than about 6 in. of steel were probably safe as close as 900 yd.

3. In Test B between 10% and 50% of the total quantity of fission products resulting from the explosion were deposited in the waters of the Lagoon. At Mike Hour plus 1 hour, the intensity at the surface of the Lagoon near the center was about 400R/24 hr. The target ships were covered topside with extremely large amounts of highly active material so that a ship at a distance of 2000 yd northeast had an intensity of 1200R/24 hr at Mike Hour plus 1 hour. The area over which the gamma dose exceeded 400 R extended 1800 yd upwind and more than 4000 yd downwind. Present decontamination methods are unsatisfactory for removing

more than a small part of this radioactive material.

4. The active material in the Lagoon water was absorbed by fish and other marine life in large quantities. Mortalities from the radiation were observed in some of these species.

5. The nuclear radiation effects from both air and underwater explosions have been shown to be extremely dangerous at great distances. Except for methods of avoidance, such as wide dispersal and increase in speed of the units, the best methods of minimizing the effects are to increase the armor protection of personnel, install air conditioning, and perfect methods of reducing surface contamination.

B. Introduction.

1. For both Tests A and B a large number of projects were carried out to measure the nuclear radiation effects resulting from the explsion. Some of these projects were carried out solely to obtain information on the effects from the bomb, but others were originated primarily to protect all personnel during the tests and secondarily, to obtain data for later analysis. A brief summary of the projects which were activated is as follows:

a. Gamma Radiation

Project No.	Project
IV-8	Gieger Counter Transmitters - Telemetering counters were installed on a number of target ships, at a depth of 100 ft to measure the gamma ray intensity in highly active areas.
IV-17	Drone Boat Operation - Drone boats entered the target area to collect water samples for radiochemical analysis and to report by means of telemetering counters the gamma ray intensities.

Project No. (con't)	Project
V-1	Destroyer Monitors - Destroyers equipped with surface and subsurface counters carried out safety patrols of the ocean downwind and downcurrent of the Lagoon and later within the Lagoon itself. Their measurements were also useful in the determination of the downwind movement of the radioactive material, the extent of the fallout, and the movement of underwater contamination.
V-2	Seaplane and Helicopter Monitors - Planes equipped with counters were used to measure the radioactivity over the target area and the islands of the Lagoon. The measurements made by the seaplanes were used to estimate the activity on the surface.
V-3	Boat Monitors - LCPLs with monitors equipped with counters were used to delimit the contaminated areas of the Lagoon and collect water samples for radiochemical analyses.
V-4	Boarding Parties - Monitors with counters were used to board target ships, measure the extent of the activity in all parts of the ship, and assist in determining the effectiveness of any decontamination procedures. Their primary mission was to assure the safety of all personnel, but at the same time they procured a great deal of information on ship contamination.
V-5	Fixed Base Monitors - Monitors were placed on a number of nearby islands to determine the radioactivity on returning planes and equipment.
V-6	Gun Boat Monitors - Same as V-3. These ships were also equipped to take samples at different depths in the Lagoon.
V-7	Channels around Bikini - In Test A instruments were placed in various channels of the Lagoon to measure any movement of radioactive material out of the Lagoon.
V-8	Air Monitors - Counters were placed in all planes in the area to prevent their entrance into dangerous spots. Planes were also used to follow the downwind movement of the active cloud.

Project No. (con't)	Project
V-9	Photometric Film (Casualty Badges) -- Film badges were placed on all target ships to measure the gamma dose both in the open and at different locations in the ships.
V-10	Radiation Intensity by Sonne Strip Cameras - These instruments were to measure the gamma intensity at different times and locations.
V-11	Radiation Intensity-Time Inside Target Ships - The gamma intensity-time relationship was determined with these instruments in a number of target ships.
V-12	Gamma Ray Intensimeters - These instruments were used to measure the gamma ray spectrum and the absorption by steel on 14 target ships.

b. Neutron Flux

V-11-2	Neutron Flux from Sulphur and Calcium Phosphate Pills - The fast and slow neutron fluxes were measured by determining the induced activity in sulphur and calcium phosphate pills placed on a number of target ships.
V-11-2	Neutron Flux from Gold Foils - Gold foils were placed on a number of buoys in Test B to determine the slow neutron flux.
V-11-2	Neutron Flux from Lithium Fluoride Tablets - Attempts were made in Test A to measure the neutron flux with lithium fluoride tablets.
V-11-2	Radiochemical Analyses of Water and Ship Materials - The slow neutron flux was measured by determining the induced activity in a number of chemicals, such as arsenicals and sodium compounds, from target ships and from the sodium in sea water.

c. Marine Biology.

1. Fish and other marine specimens were collected to determine the effect of the nuclear radiation on this type of organism.

2. Preliminary detailed results on many of these projects

have been included in the A1, A2, and B1 reports, and in appendices on file in the office of the Technical Director. There is still a considerable amount of information which must be analyzed, and as a consequence many of the conclusions presented herein may be subject to revision.

C. Purpose.

1. The objective of the measurements made by the Radiological Safety Section was to determine the effectiveness of an atomic bomb, in producing casualties from the nuclear radiation phenomena. This included an investigation of the quantities of both the gamma rays and the neutrons from the explosion, and a study of the problems created by deposition of radioactive materials on the ships. It was desirable to analyze these effects as a function of distance from the point of detonation and location on the different types of vessels. Comparison of the results obtained by exploding the bomb above the surface and under the surface was a part of the program. The effect on marine life was also to be investigated.

D. Source of Nuclear Radiation.

1. As a result of the explosion of an atomic bomb, large quantities of neutrons, gamma rays, and radioactive atoms, are spread over a very wide area. They result in the following ways:

a. Gamma rays.

1. High energy gamma rays are emitted as a direct product of the fission reaction. These rays are generated only during the first microseconds after the detonation.
2. High energy gamma rays are emitted as a result of neutron capture.

3. Gamma rays are emitted by the radioactive fission products. Certain fission products have an extremely long half-life so that a mixture of fission products can be expected to emit gamma rays for a long time. The rate of decay of a mixture of fission products may be considered to follow approximately $1/T^{1.3}$ law, where T is the time after detonation.

b. <u>Neutrons.</u>

1. Neutrons are emitted in large quantities as a result of the fission reaction. Only a small proportion of the total quantity ever gets out of the bomb itself, but nevertheless a large number escape and can be detected at considerable distances. Initially these neutrons are fast (high energy), but they are rapidly slowed down by the bomb components and the surrounding air. Water is very effective in slowing down the neutrons.
2. Delayed neutrons are also emitted by certain fission fragments. These however are a small fraction of the total neutron flux from the bomb.

c. <u>Radioactive Atoms.</u>

1. The products of the fission reaction consist of radioactive atoms of many different elements. Radioactivity will be present in the target area from fission products which may have been deposited after the explosion. Both beta particles

and gamma rays will be emitted by these artificially radioactive elements. Unless fractionation of the fission product mixture occurs, the decrease in activity should follow approximately a $1/T^{1.3}$ decay law.

2. The neutron flux resulting from the bomb will induce radioactivity in the ships and water. The three important neutron absorbers in sea water are hydrogen, sodium, and chlorine, but the only element which in practice need be considered from the point of view of residual induced activity is sodium 24, which has a half life of 14.8 hr. At short ranges activity may be induced in the steel of the ships and at somewhat greater distances in certain supplies on board such as salt and soaps (Na), arsenicals (As), etc.

3. If it is assumed that the bomb is not 100% efficient then it must be realized that any radioactive component of the bomb will also be deposited in the area in the same way as fission products. These may be detected by the alpha particles which are emitted.

E. Distribution of Radioactivity after the Explosion.

1. Test A.

a. Practically all of the fission products resulting from the explosion were carried by the tremendous heat up from the surface of the water in the cloud and moved off downwind at altitudes up to 35,000 ft.

Due to the variable wind velocities at altitudes between 15,000 and 25,000 ft, the active material was spread over a wide area. Some was rained to the surface between 60 and 90 mi east and northeast of the Lagoon between 7 and 15 hr after the detonation. The amount of radiation which was detected on the surface was below the tolerance levels and of no physiological significance. Analysis of the meteorological data obtained during the test indicated that this material probably was originally carried by the heat from the explosion to 15,000 to 25,000 ft, settled slowly, and then fell to the surface in rain. Radioactive material was detected in appreciable amounts in the air between Mike Hour plus 13 and Mike Hour plus 17 hr about 70 mi away in a generally northeast direction. Details of the growth and movement of the radioactive cloud are given in reference (1).

b. The radioactivity observed in the water after the Test A explosion was relatively low and almost entirely due to neutron induced activity in the sodium. Analyses indicate that on A Day the fission product activity in the Lagoon was less than 0.1% of the total activity of the explosion. At Mike Hour plus 4 hr a 0.8 mi^2 area roughly centered about the point of detonation contained an intensity of 0.5R/24 hr. The intensity of the activity fell off quite rapidly due to the 14.8 hr half life of sodium and the diffusion of the waters of the Lagoon, so that by 1200 on A Day plus 1 day no areas with an intensity greater than 0.1R/24 hr could be observed. For details see reference (2).

c. The residual activity on the target ships was likewise low in Test A and primarily due to neutron induction. As a consequence, on only 13 ships were intensities greater than 0.1R/24 hr observed on A Day plus 1 day. The 3 most highly radioactive ships which remained afloat on A Day plus 1 day were the SKATE, ARKANSAS, and the SAKAWA, which sank during that morning. An iron bit recovered from the sunken GILLIAM had a high induced activity. For details see reference (3).

d. Since the unreacted components of the bomb would be distributed in the same way as the fission products, no appreciable amounts were deposited in the water or on the target ships. They were dispersed downwind in the radioactive cloud.

2. Test B.

a. In direct contrast to the situation in Test A, a large portion of the fission products resulting from the explosion were deposited in the water. Calculations of the amount of radioactivity left in the Lagoon have been made on the basis of samples collected throughout the Lagoon at several depths until B Day plus 8 days. The results indicate that between 10% and 50% of the total radioactive material produced by the explosion remained in the water. At Mike Hour plus 1 hour this amount is roughly equivalent to the radiation from several thousand tons of radium. Details of these results are given in references (4) and (5).

b. Comparison of the readings obtained at various depths during the early stages indicates that the largest part of the radioactive material was initially deposited on the surface of the water, and that little, if any, was present near the bottom. This would mean that most of the water contamination resulted from the rain and spray which covered a large part of the target area for a considerable time after the detonation. A rough outline of the area, which was covered by this rain or base surge is included in Figure 5, from which it will be seen that this area extended about 1800 yd upwind and even greater distances down and crosswind. The northern reef of the lagoon was apparently subjected to this rain, but the path of the cloud lay between Amen and Bikini Islands, so that the only land contamination occurred on the northwestern tip of Bikini. Since no radioactivity was detected on the surface of the ocean north of the Lagoon by destroyers which crossed beginning at Mike Hour plus 5 hr, (see reference (6)), it was impossible to determine exactly the downwind limit of the rainout. Apparently this did not occur in large amounts very far outside the Lagoon.

c. After the radioactive fission products were deposited on the surface, they gradually diffused horizontally and in a vertical direction. Estimates based on surveys by PBMs indicated that at Mike Hour plus 1 hr the intensity of the Lagoon water near the center was approximately 400R/24 hr. (See reference (7)). Due to the prevailing southeast winds during the first 2 days after the explosion, the surface material was carried northwest, and some was skimmed off over the northern reef. Rough calculations (see reference(8)) indicate that actually a maximum of 10% of the total activity in the Lagoon escaped over the reef in this manner, and that in all probability the amount lost was very much less. The radioactive material which reached lower depths moved southeast toward Enyu Island and eventually forced non-target ships in this vicinity to move their anchorage. After B Day plus 5 days no intensities greater than 0.1R/24 hr existed anywhere in the waters of the Lagoon. However, the water was still sufficiently active to seriously contaminate the evaporators and hulls of non-target ships.

d. Bottom samples collected beginning on B Day plus 6 days showed extremely high activity in the center of the target area and even appreciable amounts throughout most of the Lagoon. Near the center the radioactive material was concentrated in a layer of newly deposited fine sand and mud about 4 to 8 in. deep. The radioactivity measured in one core sample is shown in Figure 7. One observation made with the probe indicated that the radioactive mud layer might in certain spots be even much thicker. In view of the high activity observed on coral which rained out on a number of target vessels, it is quite probable that the bottom material scoured up by the blast and redeposited was the main source of contamination on the bottom during the early stages. There was no evidence of activity in the bottom material underneath the new deposit. Even the lower layers of freshly deposited material were not highly radioactive. During the later days and outside the immediate target area absorption of radioactive material from the water by plant life probably accounted for appreciable amounts of the bottom activity. The inner shores of the Lagoon also collected appreciable amounts of radioactivity as a result of successive evaporation and absorption from the water.

e. The fission products which did not remain in the water were carried as high as 9600 ft and moved downwind (northwest) in the visible cloud. On B Day plus 1 day no significant radioactivity could be detected in the air downwind. (See reference (6)).

f. The unreacted components of the bomb were deposited in the same way as the fission products, so that wherever fission products were detected the former may be assumed to have been present also. However, experiments on some ships showed that washing procedures might remove fission products without removing the unreacted components. The presence of these components was determined analytically in above tolerance concentrations in samples collected from a number of target ships.

F. Lethal Effects of the Radioactivity from the Bomb.

1. Lethal radiation dose

a. The effectiveness of gamma rays in producing casualties has been a subject of intensive research over a period of many years, and has been particularly investigated during the war. As a result of these studies, it has been possible to estimate the lethal doses, and the doses required to give certain physiological effects. This information has been summarized in Figure 1. From this graph it may be seen that the median lethal dose for total body exposure is approximately 400 R and that doses greater than 100 R may produce radiation sickness. Doses less than 20 R will probably have no physiological effects.

b. The neutron flux required to produce casualties is not as yet so well fixed, but the best available information at present indicates that 5 x 10^{11} slow neutrons/cm^2 and 1 x 10^{11} fast neutrons/cm^2 are equivalent to approximately 400 (median lethal dose total body exposure).

c. The physiological reactions resulting from exposure to radiation are much slower to take effect than those from blast, heat, etc. A person receiving a dose of 350-400 R may suffer some nausea within 30 to 60 min, but then may apparently recover and death may not result until 6 weeks to a year later. With a dose of 450-500 R the symptoms will occure more rapidly and death occur 6-8 weeks later. An exposure to several lethal doses may result in nausea within 15 min, and death within a few days.

2. Test A.

a. Since the deposition of fission products was relatively slight, practically the entire gamma exposure on the target ships occurred in the period immediately following the detonation, and resulted from the fission reaction and extremely short lived fission products. Experiments showed that the intensity fell from greater than 10^5 R/hr to 10 R/hr in the first 40 sec. Since this radiation originated at or near the point of detonation, the gamma ray dose in the area should be distributed approximately symmetrically around this point, although some variation might be expected at short range. For details see references (9) and (10).

b. On the basis of the film badges placed on the target ships it has been possible to calculate the gamma ray dose as a function of distance from the point of detonation. These results which are summarized in Figure 2 show that without protection from steel, water, etc., the gamma rays will be lethal at a distance of about 1400 yd. Preliminary estimates of the obsorption coefficient of steel for the gamma radiation show that the half distance in steel may vary from 2 cm to greater than 5 cm. Results on the ARKANSAS show that personnel protected by the armor would be relatively safe despite high intensities topside. DDs, on the other hand, are practically transparent to gamma radiation. Final analysis of all the data, including that from the gamma ray intensimeters, should give a much more accurate figure of protection offered by the steel. (See Reference (10).

c. The slow and fast neutron fluxes have been determined using calcium phosphate and sulphur pills and from a number of other chemicals. The results obtained in Test A are summarized graphically as a function of distance in Figure 3. From these it will be seen that the slow neutrons were lethal in the open at a distance of 500 yd, while the fast neutrons were only lethal out to 400 yd. Preliminary estimates on absorption by steel were made and these indicate a half thickness of 3 in. for fast neutrons and 1 in. for slow ones. The complete data are included in Reference (11).

d. The combined physiological effects of gamma rays and neutrons have been estimated on the assumption that they are strictly additive. The thickness of steel shielding required to reduce the nuclear radiation dose to 400, 100, and 20 R has been calculated and plotted in Figure 4 for two operational conditions, i.e., personnel shielded at time of detonation and thereafter, and personnel in open at time of detonation but protected by shielding within 1 sec. Since these calculations have been made assuming a half-thickness of 1½ in. for gamma rays, 3 in. for fast neutrons and 1 in. for slow neutrons they may be subject to considerable revision when more accurate absorption data are available and should be used only as an illustration of the nature of the effects which might be expected. Roughly these data indicate that the neutrons never contribute appreciably to the total radiation effects either in the open or behind steel shielding.

3. Test B.

a. In contrast to the airburst explosion the gamma dose resulting from the underwater explosion was accumulated more slowly. Since most of the gamma rays resulting from the initial detonations were absorbed by the water, the extremely high doses, which were obtained on the decks of a large number of the target ships resulted from the fission products present in the cloud and base surge which spread out over the target ships. The total gamma dose on a ship is obtained mainly in two ways, (1) radiation from the fission products in the mist surrounding the ship, and (2) radiation from the fission products actually deposited on the ships. Since the area which was covered by these products is dependent upon the wind velocity, the gamma dose is not a simple function of the distance from the center as in Test A. The results obtained from the film badges placed on the target ships are plotted and the lethal and casualty areas have been outlined in Figure 5. These values include the dose which would have been accumulated over the period of 10 to 15 days after B Day, since it was impossible to collect the badges any earlier. However, the extremely rapid decay of the fission product mixture implies that the largest part of this dose was obtained during the first hour. In fact preliminary calculations indicate that lethal doses were obtained on many ships within 1 - 2 min. From this chart it will be seen that the lethal area in the open extends 1800 yd upwind and probably more than

4000 yd downwind. Doses greater than 8000 R existed within 1000 yd of the center. (See Reference (10) for details).

b. High gamma ray intensities were measured on a large fraction of the target ships for many days after the explosion. All but 9 of the ships at anchor were heavily contaminated topside, and only 2 of the ships which were originally radioactive were below tolerence levels as late as B Day plus 15 days. On B Day plus 10 days, 35 ships still had average topside readings of greater than 1 R/24 hr. On the PENSACOLA the average topside reading on that date was about 7 R/24 hr or greater. The decreasing average topside readings on a number of target vessels, some of which were undergoing decontamination are shown in Figure 6. Detailed results of the boarding team surveys are given in Reference (12).

c. Radio-broadcasting counters which were installed on a number of target ships have shown that the gamma radiation rate of decay is approximated by a $1/T^{1.3}$ law. Actual readings of 800 and 350 R/24 hr were obtained on ships at 2000 yd on the northeast and east respectively at Mike plus 1 hr. By using these decay curves it has been possible to make a rough calculation of the doses which would have been obtained on these ships from the material deposited on the ships. A few samples of these calculations are shown in Table I. Details of the results obtained with these telemetering counters are given in Reference (13) and (14).

d. The gamma intensities below decks were very much less than those topside, because fission products were unable to penetrate into the ships which were completely closed up. In a few cases, however, where ports had been inadvertently left open, or damage from Test A had made

TABLE I

Gamma Dose From Material Deposited on Target Ships

Ship	**Location**	Readings **Time**	 **Reading**	1st Hour Dosage*
LCT 874	2000 yd NE	M 78"	760 R/24 hr	345 R
LCT 874	2000 yd NE	B 4 day	4 R/24 hr	415 R
LCI 332	2000 yd E	M 78"	285 R/24 hr	140 R
CASCCADE	750 yd S	B 5 day	23 R/24 hr	3500 R
PENSACOLA	500 yd SW	B 8 day	14 R/24 hr	3850 R
PRINZ EUGEN	1500 yd SW	B 8 day	8 R/24 hr	2200 R
BRACKEN	1800 yd SE	B 10 day	1.2 R/24 hr	460 R

* These doses calculated upon following assumptions:

(1) Fission products were deposited on ships at Mike Hour plus 1 min.

(2) The rate of decay followed as $1/T^{1.3}$ law between Mike Hour plus 1 min and time reading was taken.

(3) All radiation was obtained from the deposited fission products.

good sealing imposible, high intensities were observed below deck as well. It seems quite probable that had ventilators been working and the ships been in normal operating condition the interiors would have been seriously contaminated. This would have created an almost insoluble decontamination problem.

e. While submerged submarines were not subject to rainout of the fission products, they nevertheless accumulated large amounts of radioactivity from the surrounding water. However, it is quite likely that had these submarines been removed from the area shortly after the detonation they would not have been seriously contaminated. The total gamma dose within one submarine was only 22 R up to the time it was surfaced and the ship opened on B Day plus 9 days, although nearby ships had doses of over 1000 R.

f. Decontamination operations met with some limited success during the early stages, since some of the loose material could be washed off with sea water. However, the reduction in radioactivity from subsequent treatments was extremely slow despite vigorous attempts at scrubbing with lye, foamite, and acid (see Figure 6). Blasting with sand or soft grits did serve to remove much of the active material from the small objects but this procedure appeared limited to clearing local areas. (See Reference (12)). Studies which have been carried out on the absorption mechanism involved in this contamination, indicate that ion exchange may be playing a part (See Reference)15)).

g. In addition to the decay curve which has been obtained from the telemetering counters (See Reference (13)), curves have been determined for samples of sea water and for a number of different materials collected around the area. These include paint, scrapings and a cable cover from the MUGFORD, oil from a slick near Bikini, contaminated soil samples, etc. Unfortunately most of these materials were not collected until several days after B Day, so that no one complete curve describing the decay rate is available. However, it is of interest that in almost all cases the slope describing the decay rate is, within experimental error, the same for the different samples. This is an indication that little selective absorption of particular fission products is occurring. Samples of these decay curves are shown in Figure 8.

h. The slow and fast neutron fluxes at a given distance from the point of detonation were considerably reduced in Test B due to the slowing down and absorption of neutrons by the sea water, and the lethal effects can be neglected. The induced activity in the sodium was probably considerably greater than in Test A, but only a relatively small fraction of the total activity in the water, (because of the large quantities of fission products) deposited on the surface. One analysis indicated that at Mike hour plus 1 day approximately 20% of the activity of a water sample was due to the sodium. After 2 days the relative importance of the induced activity became appreciably less. No induced activity was noted on ships which remained afloat.

G. Effects on Marine Life (See Reference (16) for details)

1. Test A.

a. The amount of radioactivity in the water in Test A was insufficient to cause any visible damage to the fish population or to algae and plant life.

2. Test B.

a. Many of the fish which were collected after the underwater explosion contained large amounts of accumulated radioactive material. Counts as high as 90,000/min were measured in a 0.01 gram sample. The fish which were collected near the target shortly after B day showed that the largest part of the active material was concentrated in the gills and skin. The fish which were later collected in the area northeast of the target center had the highest concentration in the digestive tract.

b. Clams, snails, and coral collected along the northern reef also showed accumulated radioactive material, and mortalities among the fish, clam, and sea urchin population were observed. Coral samples with living polyos contained more active material than samples from the same location where the coral was dead.

c. Algae collected from the Lagoon contained extremely high activity indicating that they were excellent absorbers of fission products. The fouling on ships bottoms contained active material which resulted partly from the absorption from the water and partly from the accumulation of planktonic organisms.

H. Summary and Conclusions.

1. The gamma radiation resulting from the explosion of an atomic bomb approximately 500 ft above the surface of the water will produce mortality in the open within about 1400 yd from the point of detonation and produce casualties as far as 1800 yd. Personnel protected by 6 in.*

of steel would survive the gamma radiation at distances beyond 900 yd.

2. No serious residual radioactive effects would result from the above water detonation. Contamination in the water itself would not provide a hazard to wartime naval operations.

3. The residual radioactivity resulting from the explos- an atomic bomb approximately 100 ft under the surface would present an extremely serious hazard to personnel within 1800 yd in all directions and much greater distances downwind. The exact pattern of the danger area would depend on the meterological conditions existing just after the detonation. The lower the wind speed the more nearly would the area be centered about the point of detonation, and the higher would be the dosage in this area. Since the radiation dose is not obtained within a few seconds of the detonation as in the airburst, prompt evasive action may serve to reduce the casualties. The placement of personnel in armored compartments after the explosion and prompt action to remove the ship from the path of the base surge and cloud would undoubtedly help in borderline cases. The intensities resulting from the active fission products during the first minutes are, however, extremely high, and serious physiological damage would be liable to result before it would be possible to evacuate contaminated ships and areas. Effective methods for the removal of active materials from the ships would also reduce the danger, but lethal doses would be obtained on most ships from the mist alone. Decontamination procedures are at present unsatisfactory, and undoubtedly contamination of the ships would lay them up, even during wartime, for long periods after

exposure to an underwater atom bomb explosion.

4. The absorption of radioactive materials by marine life indicates that dangerous secondary results might occur as a result of the underwater detonation of an atomic bomb.

5. Exploding an atomic bomb below the surface of the water would undoubtedly be extremely effective in neutralizing nearby land installations in the same way as the target ships at Bikini. The movement of the highly lethal radioactive cloud downwind through a populated area would inevitably produce tremendous casualties. In Test B an appreciable part of the active materials were still dispersed in the cloud at high altitudes. Had the bomb been detonated at a slightly greater depth, the absorption of heat by the water might have been sufficient to keep all the material at dangerous levels. This type of explosion would be a very effective method of dispersing an extremely toxic material which combines the properties of a persistent and a non-persistent agent.

6. The lethal area resulting from an underwater explosion is considerably greater than from air burst and the prolonged effects of the residual activity from the deposited fission product adds greatly to the effectiveness of the sub-surface detonation. However, in some cases where the subsequent occupation of an area or ship might be desirable, the air burst might be considered more practical. Both methods are very effective in producing casualties at extreme distances.

7. Since lethal effects occur almost immediately after detonation, the effectiveness of an air burst atomic bomb in producing casualties

from the nuclear radiation, can only be reduced by insuring that ship's personnel are protected by at least 6 inches of steel. The incorporation of good neutron absorbers, i.e. elements with a high neutron capture cross section, in the armor appears desireable. Since the radiation effects from an underwater explosion result partly from deposition of active material, they can be minimized by installing positive pressure air conditioning in all vessels, and by attempting to reduce the surface contamination by the elimination of surfaces of high absorption capacity or of an irregular character. The effects from both types of explosion can be reduced by the dispersion of vessels and installations over as wide an area as feasible, in order to prevent large numbers of units being neutralized by a single bomb.

References

(1) A2 Report, 013E to 013, 23 July 1946 - Appendix VIII
(2) A2 Report, 013E to 013, 23 July 1946 - Appendix IV
(3) A2 Report, 013E to 013, 23 July 1946 - Appendix VII
(4) B2 Report, 013E to 013, 25 Sept. 1946 - Appendix V
(5) B1 Report, 013E to 013, 5 Aug. 1946 - Appendix V
(6) B1 Report, 013E to 013, 5 Aug 1946 - Appendix VIII
(7) B2 Report, 013E to 013, 25 Sept 1946 - Appendix III
(8) B1 Report, 013E to 013, 5 Aug 1946 - Appendix IV
(9) A2 Report, 013E to 013, 23 July 1946 - Appendix X
(10) B2 Report, 013E to 013, 25 Sept. 1946 - Appendix X
(11) A2 Report, 013E to 013, 23 July 1946 - Appendix XIII
(12) B2 Report, 013E to 013, 25 Sept. 1946 - Appendix VII
(13) B2 Report, 013E to 013, 25 Sept. 1946 - Appendix VI
(14) B1 Report, 013E to 013, 5 Aug 1946 - Appendix VI
(15) B2 Report, 013E to 013, 25 Sept. 1946 - Appendix XIII
(16) B2 Report, 013E to 013, 25 Sept. 1946 - Appendix XIV

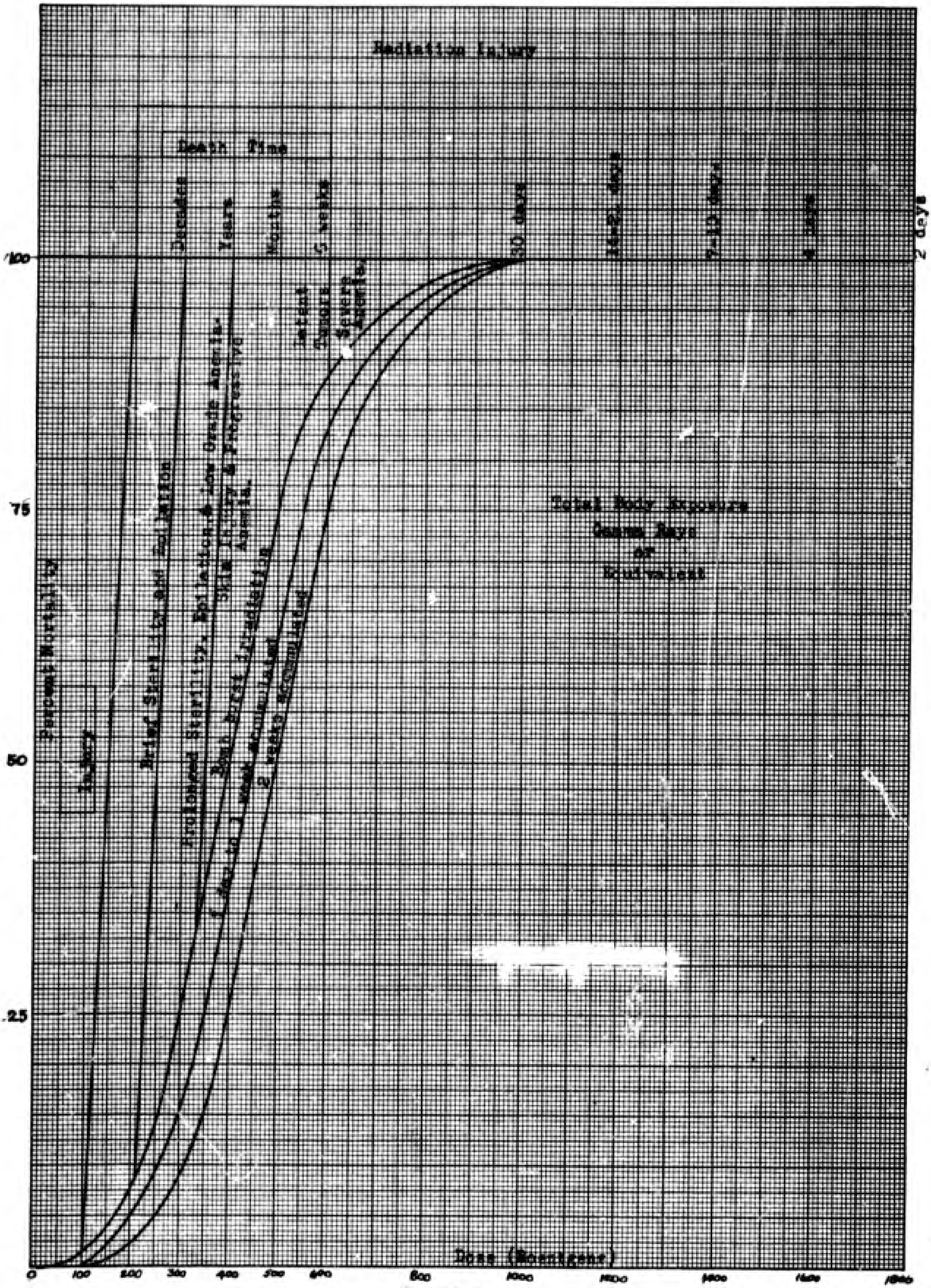
Radiation Injury
Death Time
Decades
Years
Months
5 weeks
30 days
14-21 days
7-10 days
4 days
2 days
Latent Cancers
Severe Anemia.
Brief Sterility and Epilation
Prolonged Sterility, Epilation,& Low Grade Anemia.
Skin Injury & Progressive Anemia.
Bomb Burst Irradiation
1 day to 1 week accumulated
2 weeks accumulated
Injury
Percent Mortality
Total Body Exposure
Gamma Rays
or
Equivalent
100
75
50
25
0
100
200
300
400
500
600
800
1000
1200
1400
1600
1800
Dose (Roentgens)

Figure 1

TOP-SECRET

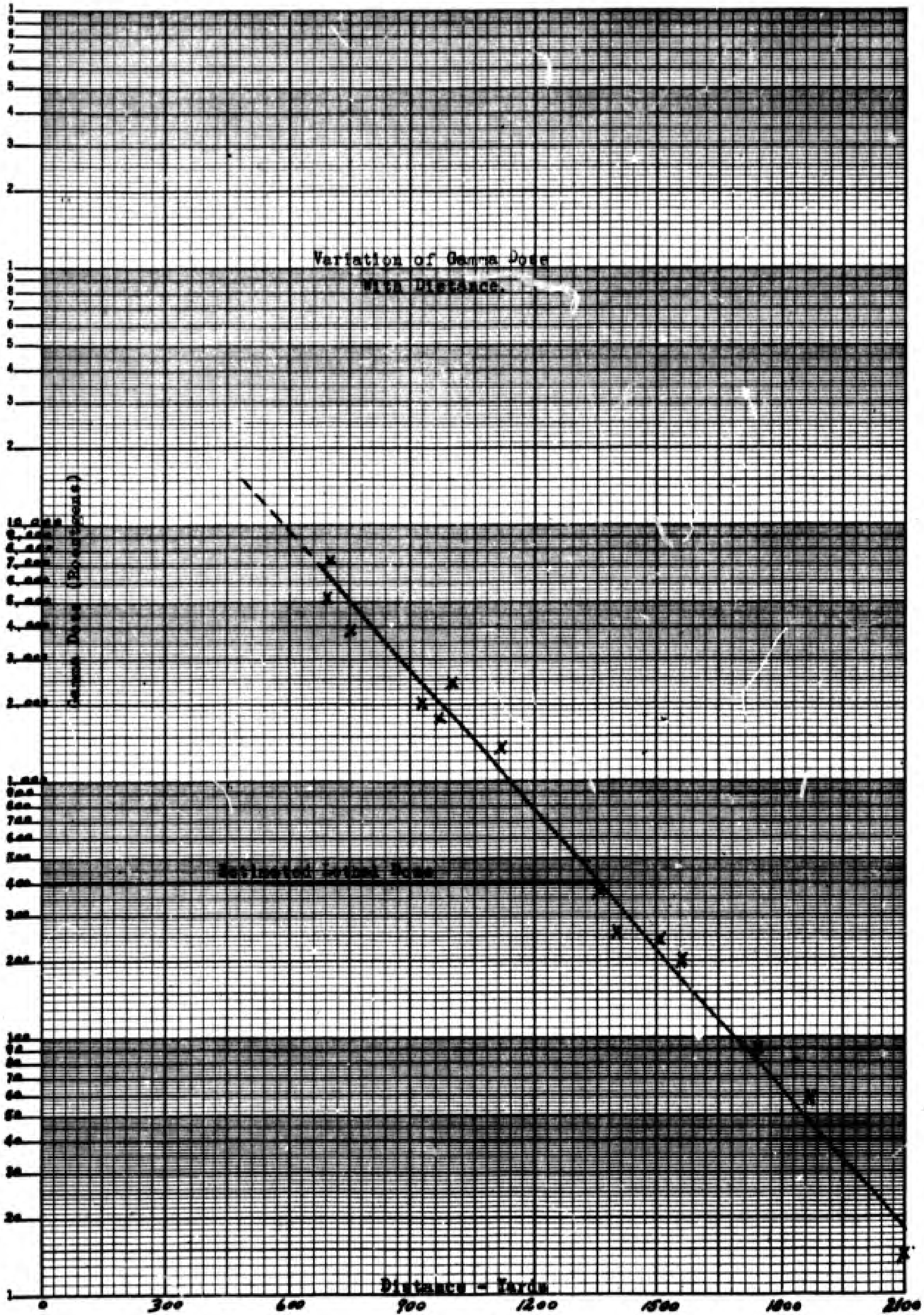

Figure 2

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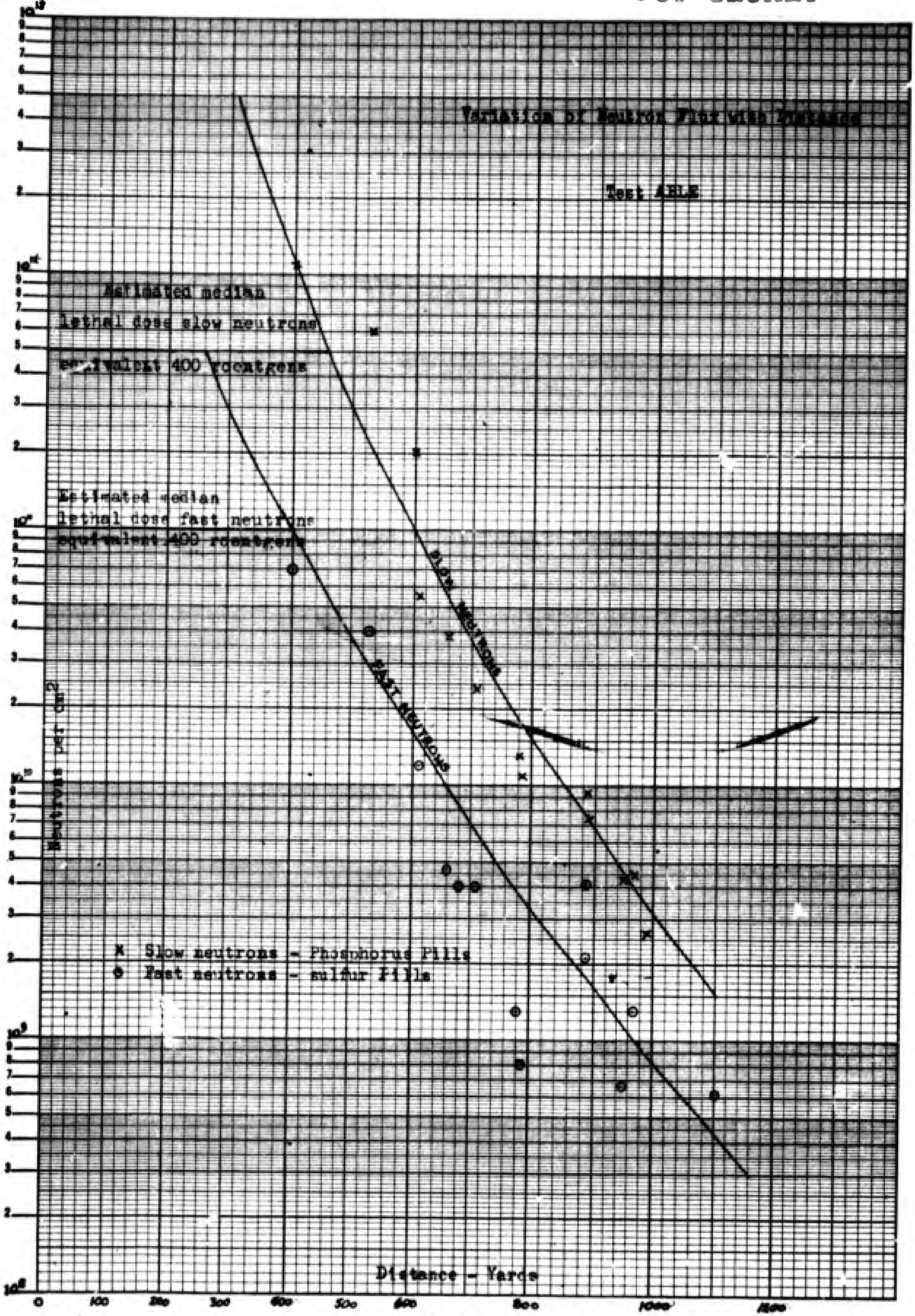

Figure 3

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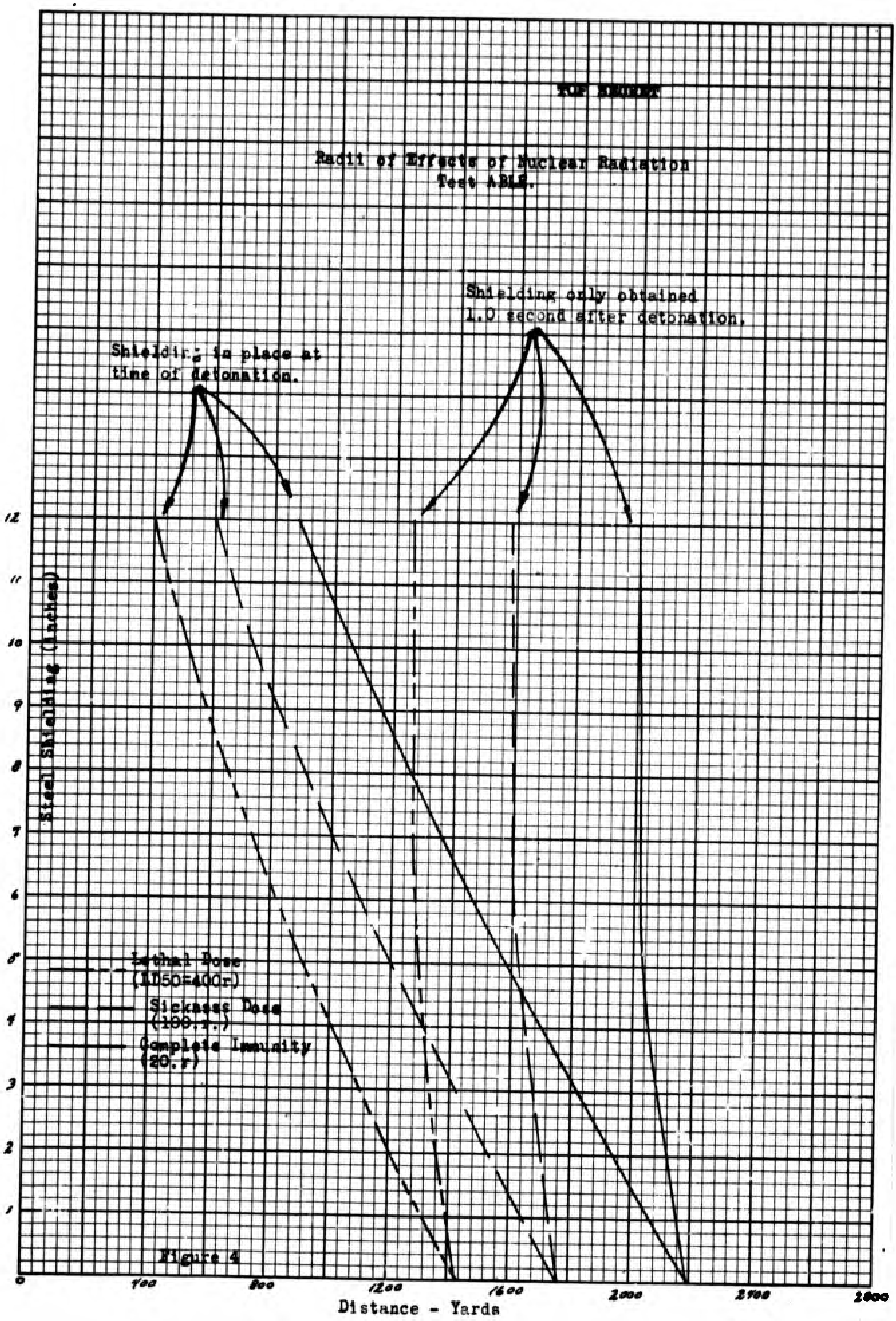

Radii of Effects of Nuclear Radiation
Test ABLE.

Figure 4

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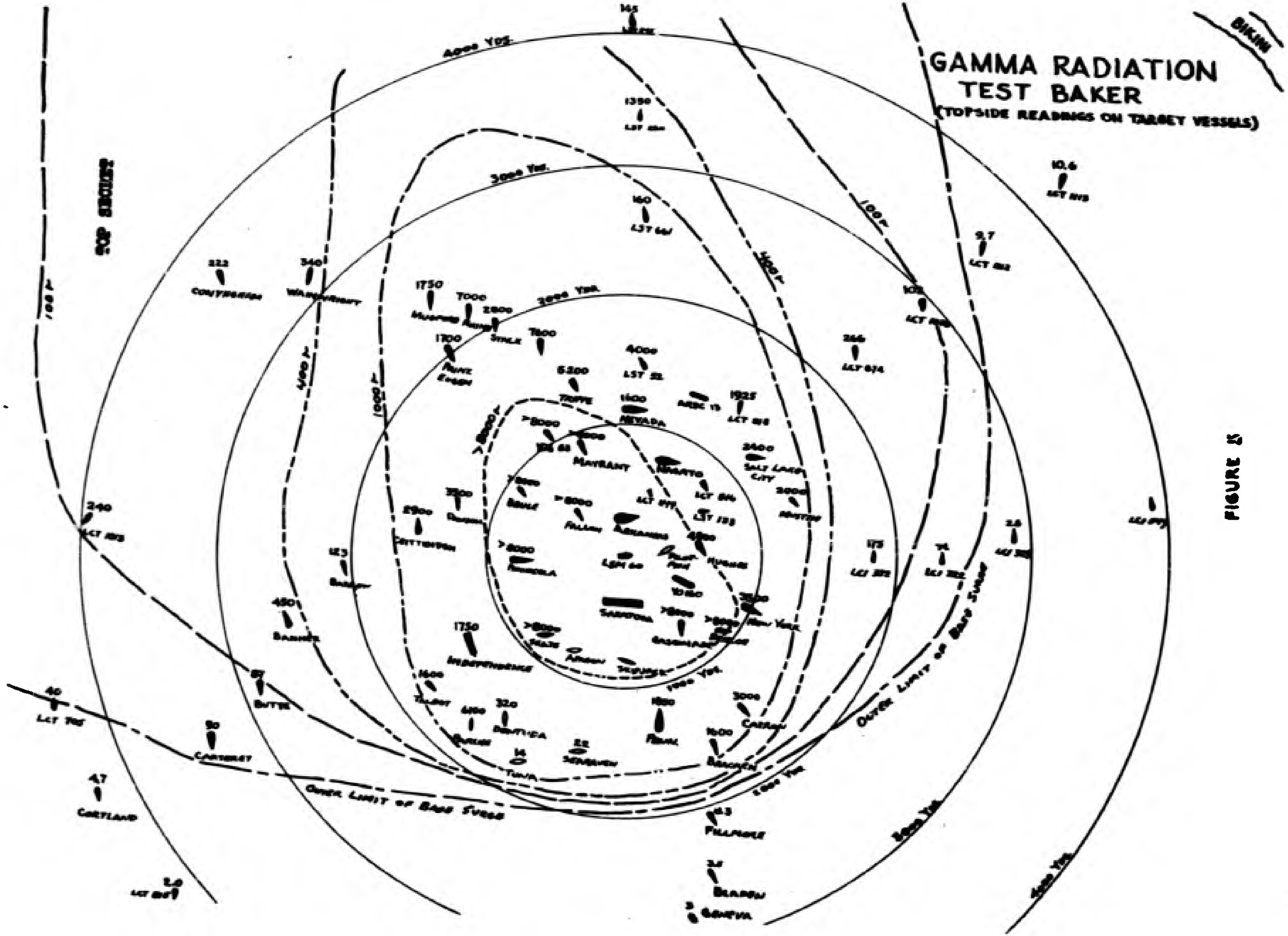

GAMMA RADIATION
TEST BAKER
(TOPSIDE READINGS ON TARGET VESSELS)

FIGURE 15

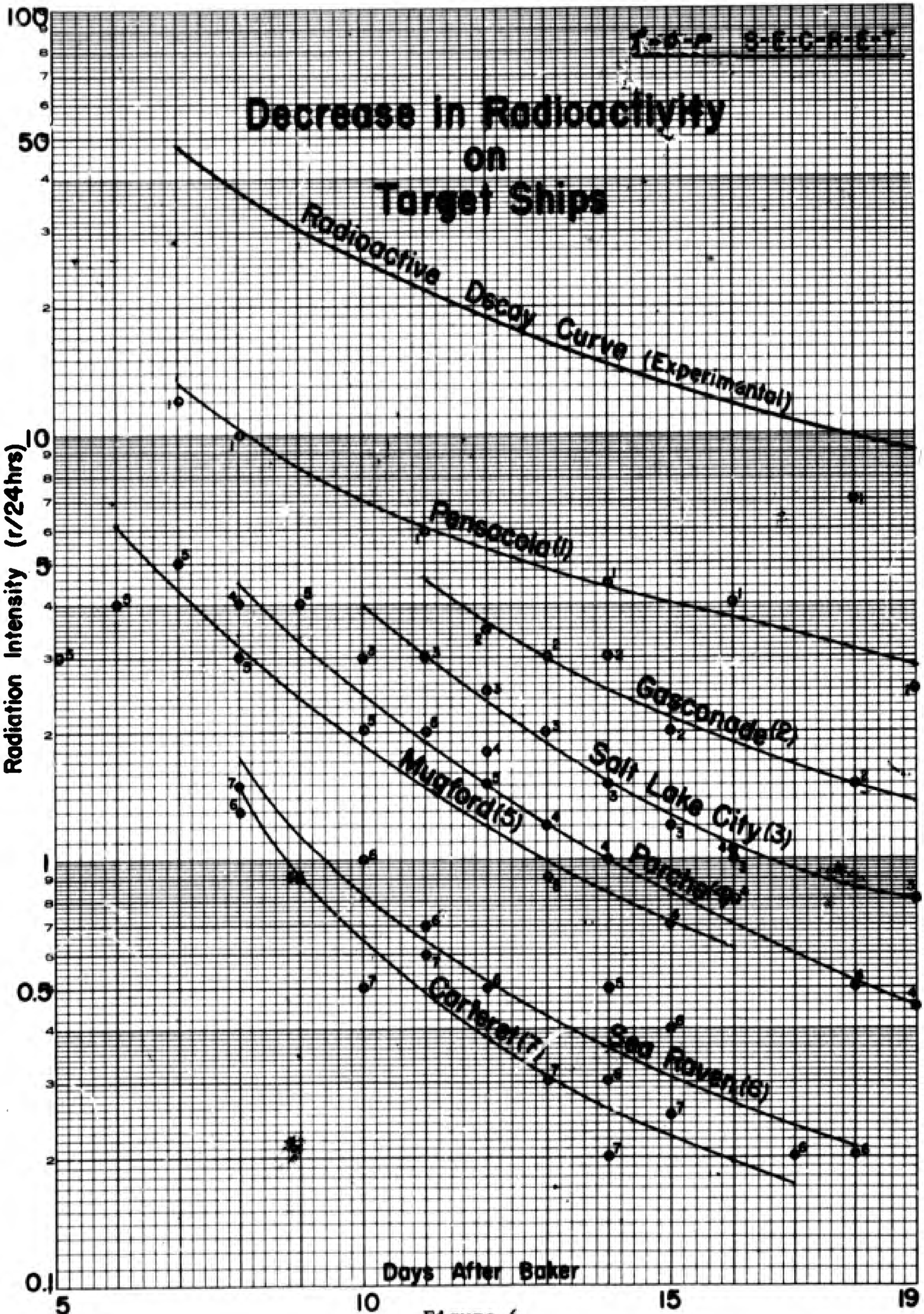
T-O-P S-E-C-R-E-T
Decrease in Radioactivity on Target Ships
Radioactive Decay Curve (Experimental)
Pensacola(1)
Gasconade(2)
Salt Lake City(3)
Porchefor(4)
Mugford(5)
Sea Raven(6)
Carteret(7)
Radiation Intensity (r/24hrs)
Days After Baker
100
50
10
5
1
0.5
0.1
5
10
15
19

Figure 6

TOP SECRET

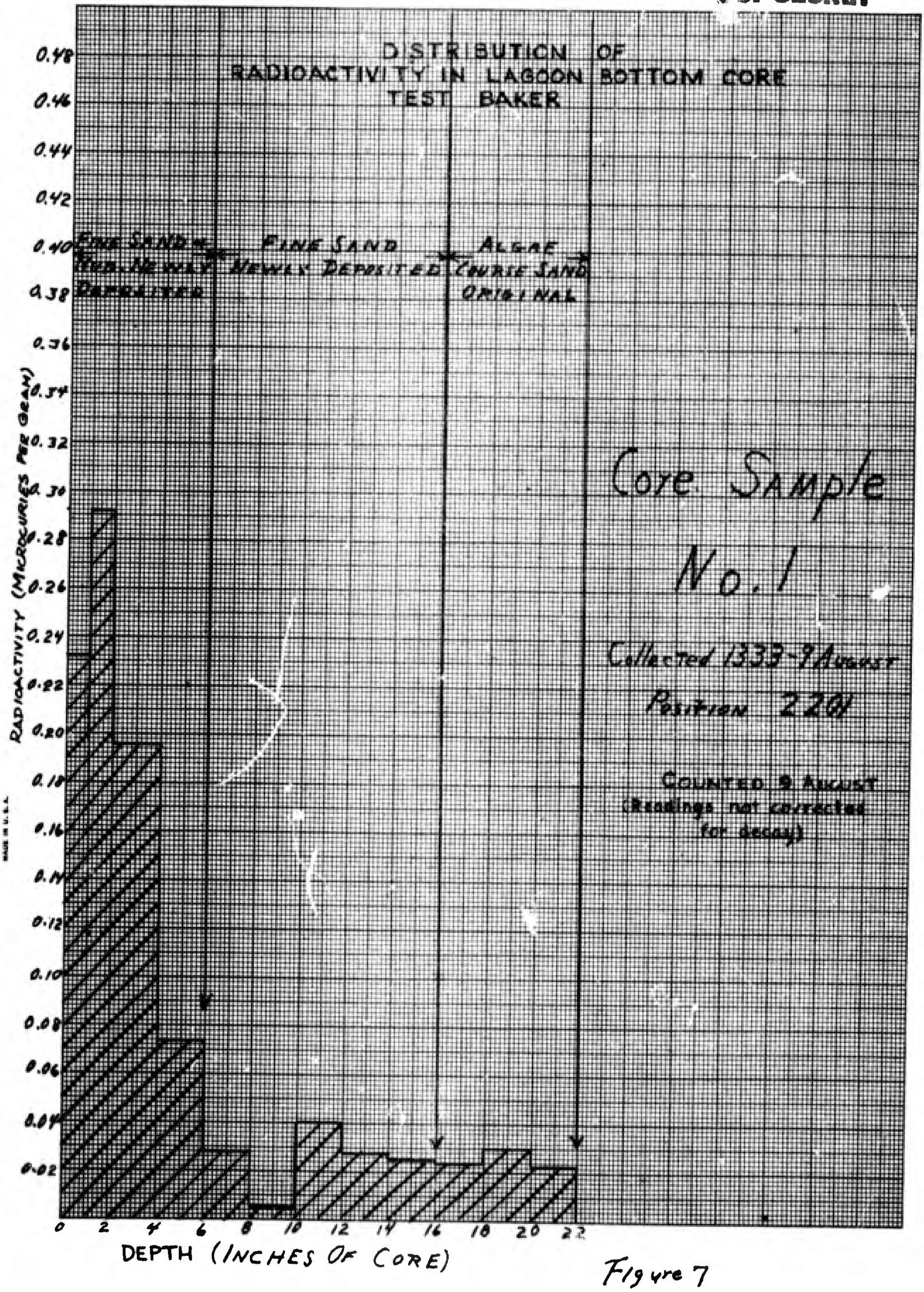

Figure 7

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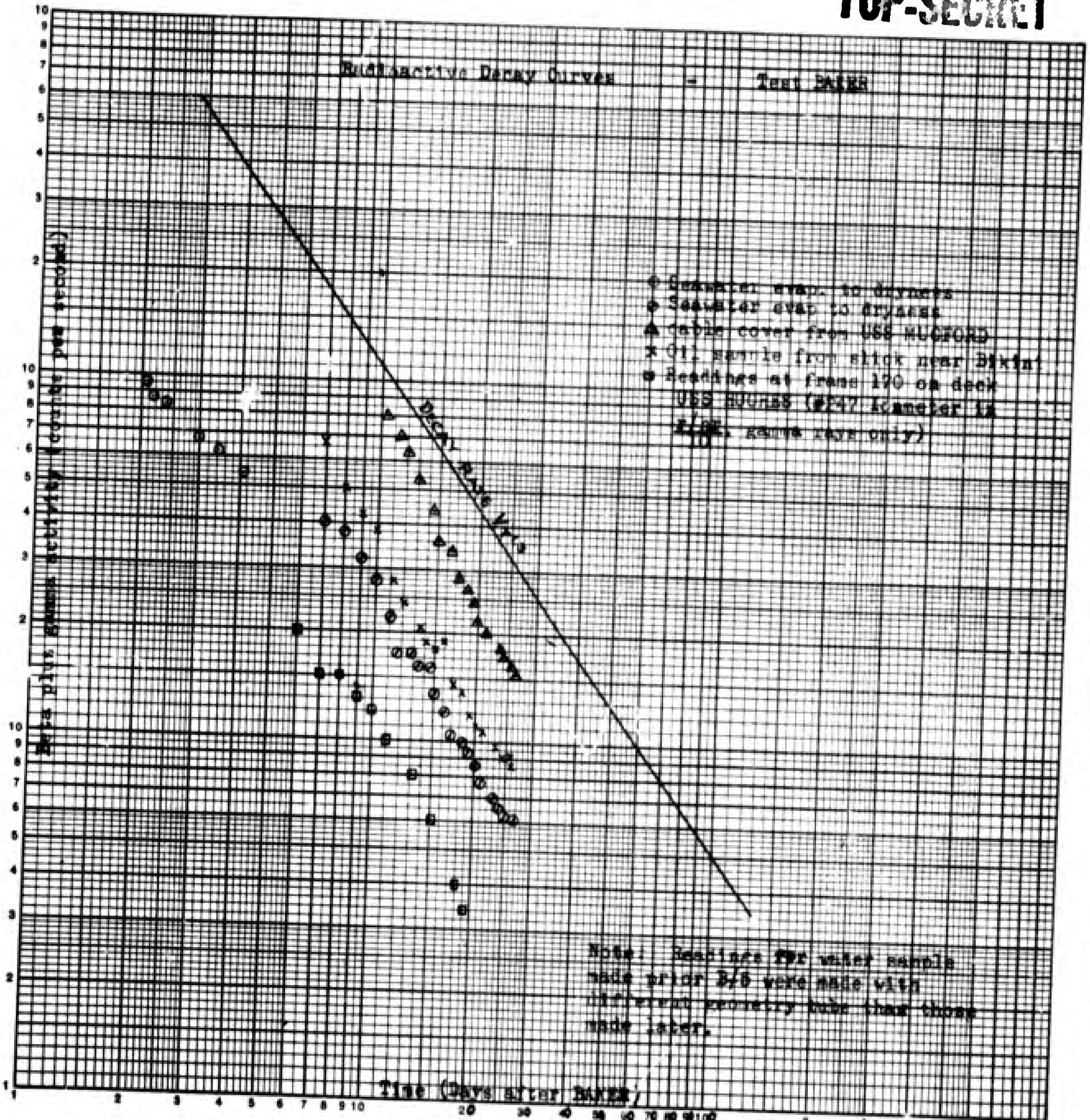

Figure 8

SECRET

ENCLOSURE K

"Preliminary Evaluations of Remote Observations of Test A and Test B"

by

Cdr. George Vaux

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Preliminary Evaluations of Remote Observations of Test A and Test B.

This report is intended to present a general estimate of the results of observations obtained during Operation Crossroads, rather than a complete presentation of individual data. This report, therefore, has been prepared in narrative form to cover the purpose in view.

Commander Joint Task Force ONE approved the proposal of the Office of Naval Research for a broad program of observations during Operation Crossroads, using instruments which are sensitive to various forms of transmitting energy. Two purposes were to be served in this investigation: (1) information of value to science might be obtained which would increase present knowledge in various fields of propagation, and (2) the more urgent problems of determining methods by which the occurence of large scale nuclear fission might be detected at great distances over the earth's surface.

A program was evolved which included not only the construction of special apparatus and the operation of stations under the immediate direction of the Office of Naval Research, but also observations by industrial, scientific, and government agencies who associated themselves in the project. Table I provides a brief outline of the types of observations made, together with the principal locations of the stations, and the agency making the observations in each case.

VIII 1-4 Seismological Measurements.

The U.S. Coast and Geodetic Survey maintains numerous seismograph stations throughout the United States and its possessions. In addition, special stations were set up at the locations listed in Table I in an attempt to record earth disturbances originated at Bikini by the detonations of Bomb A and Bomb B. In the case of Bomb A no record was obtained on any of these instruments, (except for weak P Waves observed at Kwajalein) although all apparatus were operating properly. The record at Kwajalein was barely discernable due to its low amplitude and also because of earth motion due to heavy surf. From these results, it must be concluded that an atomic bomb, when exploded above the earth's surface does not introduce sufficient energy into the earth's crust to propagate a shock wave which can be detected over any but the shortest distances by high sensitivity accelerographs or seismographs.

The results obtained from Bomb B were much more satisfactory. Records of large amplitude were obtained at most of the stations in the Pacific, and several seismological observatories in the United States also obtained records. These included Tucson, Pasadena, Boulder City and Mt. Wilson. Recorded amplitudes of the P Wave in this case are about equal to those of a shock of magnitude 5½, on the earthquake scale, at the same distance. It is therefore apparent that an underwater detonation of an atomic bomb can be detected over a considerable distance by seismographs, although further study of the records will be necessary to determine whether there are any unique features by which such an event can be distinguished from an ordinary earthquake. However, it would seem that for the second purpose outlined above i.e., the problem of long range detection, these positive results are largely of academic interest, as the likelihood of such experiments being conducted under water is rather remote.

VIII 5-8 Tidal Measurements.

Standard Tide Gauges were installed at the locations stated in Table I, in addition to the instruments in regular operation. No tidal effects were observed, distinguishable from the usual diurnal variations, which could be attributed to the disturbance produced by either Bomb A or Bomb B. It is evident that the wave disturbances reported in Bikini Lagoon were completely dissipated before reaching the nearest stations at Eniwetok and Kwajalein.

VIII 9 Terrestrial Magnetism.

The stations listed in Table 1 are in continuous operation, making measurements of magnetic declination, and horizontal and vertical magnetic intensity of the earth's field. The stations were alerted to observe carefully for any unusual deviations in these quantities. No phenomena were observed which could be attributed to Bomb A or Bomb B.

VIII 10 Atmospheric Conductivity.

Measurement of the electric conductivity of the atmosphere 8,000 ft over the Pacific Ocean off Los Angeles was made daily from 30 June 46 to 5 July 46, to determine if appreciable changes in electrical conductivity of the air occured at high altitude when an atomic bomb was exploded at a great distance. The behavior of the conductivity after the explosion was not in accordance with prior conceptions, because the only noticeable change observed was a relatively small decrease, amounting to 10%, which occurred about an hour and a half after the explosion. This affect disappeared within 2 days. It is therefore believed that preliminary results must support the conclusion that such measurements are not a good criterion for specifying the existence of such an explosion. These observations were made only on Test A.

VIII 11 Atomospheric Reflectivity.

An extensive chain of stations is operated by the Department of Terrestrial Magnetism, Cargnegie Institution of Washington, where constant measurements are being made on the height and characteristics of the ionsphere. These stations were asked to make more frequent observations during Tests A and B. Inspection of the resultant graphs revealed no effects which could definitely be attributed to atomic bomb explosions. In the case of Test B an ionosphere storm began shortly after the detonation, with the results that any small effects from the explosion would have been masked by high background conditions caused by the storm. However, from the fact that no such small effects can be found in the Test A records, it seems reasonable to assume that no observable changes occurred during Test B.

VIII 12 Atmospheric Ionization.

Two types of apparatus were employed in this investigation: (1) measured the total ionization in the air, while (2) measured only that ionization which was produced inside a chamber by the entrance of ionizing radiation. The former apparatus was installed at the first 3 stations mentioned, while the latter was installed at all stations. Unfortunately the temperature and humidity at stations in the Pacific interferred seriously with the operation of the equipment, and no great reliance can be placed on the records. At the present time it cannot be stated definitely whether these records will show anything, but it is believed that this type of apparatus could be redesigned to eliminate the difficulties introduced by atmospheric conditions, in which case it would form an important device for monitoring purposes.

VIII 13 Microbarographic Measurements.

Electromagnetic microbarographs were set up at a number of stations in continental United States on the basis of the fact that a similiar instrument recorded the Trinity Test at a distance of 700 mi, in Pasadena. Theoretical calculations of the propagation of pressure waves from such an explosion, based on an assumed initial energy, provided the belief that at distances of approximately 4000 mi. a pressure of 70 dynes/cm^2 would be observed. As this figure represents a pressure about one magnitude in excess of the normal background variation of the atmosphere, it was believed that it could be detected. However, no results were obtained which could be attributed to either explosion. The explanation of this fact may be drawn from the pressure obtained at Kwajalein which was of the order of only 100 dynes/cm^2, at a distance of about 400 mi. Making the usual calculations for attenuation and loss of energy experienced by the wave in traveling 4000 mi, it was found that the pressure would have fallen to about 10 dynes/cm^2, a pressure within the range of normal atmospheric background.

VIII 14 Microbarographic Measurements.

Navy Mark I Acoustic devises were provided with special transducer elements to couple the equipment to air. No results were obtained in the United States or Honolulu from either Test A or B. The Honolulu station was not in operation during Test A. Excellent records of the pressure wave were obtained at Kwajalein, from which the general information cited in the previous paragraph was obtained.

It is known that the sensitivity of this apparatus can be considerably increased and also that the limiting effects of atmospheric "background" disturbances can be lowered by a factor which depends upon the increase in the total number of stations employed. Therefore, although not a probability, there is a possibility that further work in this field would achieve fruitful results for monitoring purposes.

VIII 15 Microbarographic Measurements.

Sound ranging equipment, as developed by the United States Army Signal Corps was modified to include condensor microphones as the transducer elements. This device depends upon the pressure incident upon it, and is independent of the velocity of diaphragm vibration, so that it is capable of recording waves of very long periods. At the present time the data obtained is not in form from which definite conclusions can be drawn, owing to the fact that they must be correlated with meteorological information now in preparation.

VIII 16 Radio Propagation.

Although the probability of detecting any variations in radio propagation was considered remote, the Federal Communications Commission and certain Naval Communication facilities were requested to monitor a number of frequencies emanating from the vicinity of Bikini. In addition, the destroyer KEYES was ordered to take station in line with Bikini and Naval receivers in the Hawaiian Islands, for the purpose of transmitting signals which presumably would be propagated through the disturbed area. No significant results were obtained from any of these investigations.

VIII 17 Radioactive Particles at the Earth's Surface.

Geiger Counters were operated at the stations listed to attempt detection of radioactive particles which might be carried aloft by winds as far as the United States. An increase of about 35% in counting rate was observed at Puget Sound Naval Shipyard approximately 150 hours after Test A. This means that the material must have traveled with an average velocity of 25 knots from Bikini, which is an assumption well within realm of possibility. The percentage increase is somewhat disappointing, although it must be remembered that the material which affects the instrument must be carried to a considerable altitude and then be returned to the earth's surface in order to be detected. In view of the fact that this station recorded radioactive materials with a fair degree of certainty, and further that other locations on the West Coast, which were not cooperating with this program, reported similar increases, it appears that the use of Geiger Counters is one of the few possible methods of detecting large-scale fission processes at remote distances.

VIII 18 Radioactive Particles in the Upper Atmosphere.

Standard radiosonde transmitters, such as are normally used for meteorological observations during ascent into the upper atmosphere, were modified so that each carried a small Geiger Counter. The counting rate could be telemetered to receiving stations on the ground.

These instruments produced data which at first glance are somewhat disappointing, but which may provide significant results when subjected to more careful study than has been possible up to the present. It has been definitely ascertained that most of the difficulties are due to instrumental design, and many of these can be rectified fairly readily in the light of experience gained during Operation Crossroads. It is firmly believed that these devices when employed at a number of stations simultaneously can be developed into significant detectors.

General Conclusions and Recommendations.

In the light of present experience it appears that several of the fields outlined above may be eliminated as means for remote detection. Seismographs will detect such an explosion only when the explosion takes place in contact with the earth's surface. This fact therefore seriously limits the value of the device, as it is not likely that experiments with fissionable materials will be conducted under earth or water.

It is believed that further study should be given to the general field of devices for detecting pressure waves as described in VIII 13, 14, 15. It is certain that these devices will work over distances of several hundred miles, and therefore observing stations strategically located could perhaps detect explosions which were not too remote.

A stable ionization device should be developed which can be operated satisfactorily in the tropics. Background measurements should be taken over long periods. These instruments could be operated in conjunction with Geiger Counters.

The most profitable direction seems to be the modified radiosonde. Experience has determined that the mass production of these units is not an insurmountable problem, and that they could be built relatively inexpensively. It is therefore recommended that this device be redesigned to eliminate present instrumental difficulties and that a program for continuous monitoring be established on a large scale. The advantage of this method lies in the fact that observations could be made at any station where meteorological balloon flights are normally made. Hence the basis for suitable world coverage already exists and could be supplemented by additional stations located in strategic positions.

Table 1

Project Number	Type of Measurement	Location	Agency
VIII 1-4	Seismological Measurement	Wake Midway Kwajalein Honolulu Apia Guam Pacific Coast	U.S. Coast & Geodetic Survey
VIII 5-8	Tidal Measurements	Eniwetok Wake Kwajalein Midway	U.S. Coast & Geodetic Survey
VIII 9	Terrestrial Magnetism	Honolulu, T.H. Sitka, Alaska Tucson, Arizona. Cheltenham, Md. San Juan, Puerto Rico	U.S. Coast & Geodetic Survey.
		Huancayo, Peru Watheroo, Australia	Department of Terrestrial Magnetism
VIII 10	Atmospheric Conductivity	Minneapolis California	Naval Research Lab.
VIII 11	Ionspheric Reflectivity	Various	National Bureau of Standard and Dept. of Terrestrial Magnetism
VIII 12	Atmospheric Ionization	Swarthmore Seattle Mt. Wilson Austin Honolulu Wake Midway Tucson	Office of Naval Research
VIII 13	Microbarographic Measurements of Pressure Wave	Sitka San Juan Rapid City Chicago Tucson Bozeman	Office of Naval Research.

Table I (Continued)

Project Number	Type of Measurement	Location	Agency
VIII 14	Microbarographic Measurements of Pressure Wave	Kwajalein Honolulu Seattle Washington, D.C. Enyu Island USS Kenneth Whiting	Naval Ordnance Laboratory
VIII 15	Microbarographic Measurements of Pressure Wave	Grafenwohr, Germany Manila Honolulu Nome, Alaska San Francisco	U.S. Army Signal Corps
VIII 16	Radio Propagation	Various	Naval Communications
VIII 17	Measurement of Radioactive Particles at Earth's Surface	Seattle Austin, Texas Washington, D.C.	U.S. Navy ShpYd. U. of Wash. U. of Texas National Bureau of Standards
VIII 18	Measurement of Radioactive Particles in the Upper Atmosphere	Manila Guam Wake Tarawa Honolulu Medfore, Oregon San Diego Swan Island Coco Solo Denver Washington, D.C.	Office of Naval Research

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Classification (Cancelled) (Changed to S-RD
By Authority of JOINT CHIEFS OF STAFF [illegible] DATED 15 APRIL 1949
By ---------------- Date 27 June 49

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